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Mapping Surficial Geology in the New River Gorge National River and Bluestone National Scenic River, West Virginia, using LiDAR-derived Digital Elevation Data

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ABSTRACT

Mapping Surficial Geology in the New River Gorge National River and Bluestone National Scenic River, West Virginia, using LiDAR-derived Digital Elevation Data

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The purpose of this thesis was to determine if the surficial geology of Bluestone National Scenic River (BLUE) and New River Gorge National River (NERI), two areas of similar geology, can be mapped using visual interpretation methods applied to digital elevation models (DEMs) derived from light detection and ranging (LiDAR) data. Surficial geology in BLUE was field mapped using GPS, following definitions and characterizations for surficial geology units established with the guidance of Dr. J. Steven Kite. A 2m x 2m LiDAR-derived DEM was used for BLUE and most of NERI using US Army Corps of Engineers (USCOE) LiDAR data, and a 1m x 1m DEM was created using West Virginia Department of Environmental Protection's (WVDEP) Division of Mining and Reclamation LiDAR data for Babcock State Park, which is located within NERI and not included in the USCOE LiDAR dataset. The DEM was used to create a slope shade map and hillshade maps. The surficial geology was manually digitized at a 1:3,000 scale based on visual interpretation of image texture, slope steepness, and slope position. The digital mapping methods and definitions established at BLUE were then applied to mapping surficial geology at NERI. Surficial geology units defined and mapped at BLUE and NERI were: disturbed areas, river channels, floodplains, rock floored floodplains, terraces, alluvial fans, tributary deposits, bouldery tributary deposits, fluvial channels, colluvial fans, colluvial aprons, colluvial veneers, colluvial mantles, blocky mantles, landslides, rock cities, and residuum. The surficial geology units were then assessed based on the bedrock units in which they were associated spatially. LiDAR-based DEMs were found to be useful for understanding the dynamics between bedrock stratigraphy and landscape development. LiDAR-derived DEMs were effective in significantly reducing field work and in identifying and delineating surficial geology landforms.

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Introduction

Surficial geology maps delineate the extent and distribution of surficial geology units and associated deposits based on changes in slope gradient and the presence of characteristic topographic features (Jones *et al.,* 2007). These maps traditionally are made by investing large amounts of time at field sites while drawing unit boundaries onto a large-scale base map as landforms and surficial geology units are identified in the field. These efforts are often constrained by limited time, property access, and vegetation cover, which in aggregate constrain the area that can be mapped and the quality of mapping.

A high-resolution digital elevation model (DEM) generated using light detection and ranging (LiDAR), also known as airborne laser scanning (ALS), can potentially provide detailed topographic information useful for surficial geology mapping (Jones *et al.,* 2007). DEMs offer the potential for creating draft maps of the landforms prior to field work, thus facilitating optimal utilization of time in the field. In addition, field work can be planned in order to maximize time spent in areas with complex geomorphological features and minimize field time in simpler areas (Jones *et al.*, 2007). Having an office-generated draft landform map in hand allows field work to focus on validating and refining the mapping, rather than potentially haphazard raw field data collection. A DEM-based approach may result in more detailed, and potentially more accurate, final maps, while also lowering the costs involved in surficial geology mapping.

Research Aims

The purpose of this thesis is to determine if the surficial geology of Bluestone National Scenic River (BLUE) and New River Gorge National River (NERI), an area of similar geology to BLUE, can be mapped using visual interpretation methods applied to LiDAR-derived DEMs.

Previous Work: LiDAR and surficial geology mapping based on surficial geology units

Hohenthal *et al.* (2011) provide an overview of how LiDAR datasets are acquired. LiDAR technology uses an airborne laser to generate light pulses that are deflected, typically in an across-flight direction, by a scanner, thus incrementally illuminating a broad area beneath the aircraft. The laser pulses are reflected by the ground and objects on the ground, including the canopy, undergrowth, and structures, and the time of two-way travel is recorded by a sensor integral to the LiDAR system. Global positioning system (GPS) and an inertial measurement unit (IMU) location data are used to continuously record the position and orientation of the laser sensor. The recorded laser range, beam deflection, and sensor position and orientation are used to create a georeferenced 3D point cloud that represents the geometry of target objects. The point cloud is then labeled using supervised classification (Jones *et al.*, 2007) to identify the reflecting surfaces such as ground, vegetation, and structures. The ground class normally includes only last return points (Maxwell, 2010). A bare earth digital elevation model (DEM) is created by interpolating the unstructured point cloud data onto a regular grid.

The accuracy of a DEM is dependent on the accuracy of the labeling process, which like any classification, involves tradeoffs. An approach that is too conservative in identifying ground points will not capture the complexity of the ground surface and result in a smoothed DEM

(Maxwell, 2010); an approach that is too liberal will misclassify vegetation, structures, or objects on the ground as part of the topographic surface. This issue is particularly acute in areas with bouldery landforms, as LIDAR returns from these features tend to be easily confused with non-ground objects, and thus removed from the class of ground points. On the other hand, a rough texture on hillshades, an indicator of a bouldery landscape, can also be caused by incorrectly labeled points used in the surface interpolation (Maxwell, 2010). Thus, interpretation of DEM data for geomorphological mapping requires an understanding of the pre-processing used in generating the DEM.

Another challenge in using DEM data for geomorphological mapping is that different topographic features become apparent as the scale of analysis varies. Jones *et al.* (2007) addressed this concern by developing a multi-scalar approach incorporating six successive elevation classification intervals for displaying DEM data: 4 m, 2 m, 1 m, 0.5 m, 0.25 m, and 0.1 m. Jones et al. (2007) initially mapped landforms with the 4 m classification interval, and then landforms were progressively added and edited as the intervals became smaller. The multi-scale mapping process was found to be more accurate than mapping landforms at only the 4 m interval or the 0.1 m interval. The maps created using LiDAR-based DEM were compared to maps produced using field methods, and 80% of the geomorphic features mapped using only LiDAR were found to be accurate. Jones *et al.* (2007) conclude that when a high degree of accuracy is needed, maps produced using LiDAR should be verified in the field. However, using LiDAR derived maps helps to first familiarize the researcher to the field area and also focus field data collection to areas of complex geomorphology, therefore, reducing time spent in the field.

Study Areas

The study areas for this project are a subset of a larger geologic resource evaluation project of the West Virginia Geological and Economic Survey (WVGES) (Hohn, 2009), funded by tNational Park Service Geologic Resources Inventory (NPS GRI) Program as part of a national initiative to map 270 natural area park units across the United States. The larger WVGES project comprises the mapping of the bedrock and surficial geology within BLUE (Matchen *et al.*, 2011; NPS GRI program, 2012), NERI (McColloch *et al.*, 2013; NPS GRI, 2014), and the Gauley River National Recreation Area (GARI) (Hunt *et al.*, 2010; Kite et al., 2016, NPS GRI, 2016). As part of the WVGES project, personnel from West Virginia University and Concord University were contracted to undertake the bedrock mapping.

This thesis research focuses on mapping the surficial geology within the BLUE and the NERI, both of which lie entirely in West Virginia. Figure 1 shows the two field areas in relation to one another. At the request of National Park Service staff, the BLUE and NERI mapping areas were extended by a 100 m buffer beyond the mapped NPS boundary in order to provide map coverage in case the existing boundaries were inaccurately mapped or subject to minor change. The thesis research maps are available from the West Virginia Geological and Economic Survey (Yates and Kite, 2014; 2015a) and the National Park Service (Yates and Kite, 2015b; 2016).

<u>Bluestone National Scenic River (BLUE)</u>

BLUE (Figure 2) was authorized on October 26, 1988, to preserve the geological, natural, cultural, recreational, and scenic values of the lower 16.9 km (10.5 mi) of the Bluestone River (National Park Service, 2017a). BLUE has a total area of 1,744 ha (4,310 acres) within Mercer and Summers counties, West Virginia (Covington, 2005). Pipestem Resort State Park is adjacent to BLUE and also overlaps BLUE in places, and thus the BLUE map includes a major portion of that state park (Figure 2).

New River Gorge National River (NERI)

The second study area, NERI (Figure 3), was established on November 10, 1978, to conserve the natural, scenic, and historic values of the gorge section of the New River in West Virginia for current and future generations (National Park Service, 2017b). NERI totals 29,214 ha (72,189 acres) and extends approximately 85 km (53 mi) from Hinton, West Virginia, to Fayetteville, West Virginia (Covington, 2005). The NERI boundary includes all of adjacent Babcock State Park. Due to the lengthy spatial extent and variability of the NERI study area, and following the approach of Remo (1999), NERI is divided into three sections (Figure 4): the upper (Figure 5), middle (Figure 6), and lower (Figure 7) regions.

Geology and Geologic History of BLUE and NERI

Both BLUE and NERI are located in the Appalachian Plateaus physiographic province of southern West Virginia. The study areas are located within the Logan and Allegheny plateau subprovinces of the Appalachian Plateaus physiographic province (Outerbridge, 1987). Bluestone River begins in the Logan Plateau and ends in the Allegheny Plateau (Outerbridge, 1987), where the Bluestone flows into New River at Bluestone Lake (Figure 8). The BLUE study area is located within the Allegheny Plateau. The NERI study area is mostly located within the Allegheny Plateau, with the lower reaches of New River flowing back into the Logan Plateau before meeting Gauley River to form Kanawha River (Figure 8).

The Logan Plateau is bordered to the southeast by the Allegheny Plateau subprovince (Outerbridge, 1987). The Logan Plateau is highly dissected by dendritic streams with straight reaches (Outerbridge, 1987). These stream valleys are very steep and narrow, with slope gradients averaging 26º (Outerbridge, 1987). Valley floor elevation varies from 200 to 700 m (Outerbridge, 1987). Logan Plateau ridges are narrow and meandering (Outerbridge, 1987). Hilltop elevation ranges from 450 to 1050 m (Outerbridge, 1987). Relief between the valley floor and the top of the ridges varies from 150 m to 750 m with a median relief of 300 m (Outerbridge, 1987). The Logan Plateau subprovince is underlain by the relatively flat-lying, Pennsylvanian-aged Kanawha Formation (Outerbridge, 1987).

Outerbridge (1987) describes the Allegheny Plateau as not as deeply dissected by dendritic streams as the Logan Plateau. Allegheny Plateau valleys are relatively wide and flat and the hilltops are rounded with elevations ranging from 600 to 1000 m (Outerbridge, 1987). The relief between the valley floor and the top of the ridges is typically 100 to 400 m (Outerbridge, 1987).

Bluestone River originates 16 km (10 mi) west of Bluefield, West Virginia. It flows 124 km (77 mi) to Bluestone Lake, south of Hinton, where it joins New River (Covington, 2005). In the BLUE study area, the stratigraphy is Upper Mississippian to early Pennsylvanian in age (Englund and Thomas, 1985; Matchen *et al.*, 2011; NPS GRI program, 2012). The Hinton and Bluestone formations are dominant in this area (Matchen *et al.*, 2011; NPS GRI program, 2012). The Hinton Formation is largely calcareous shale and siltstone with minor amounts of gray shale, sandstone, limestone, and coal (Englund and Thomas, 1985). It is disconformably overlain by the Princeton Sandstone, which is characterized by a conglomeratic base that fines upward into light-gray, fine- to coarse-grained calcite-cemented sandstone that is thickly bedded (Englund and Thomas, 1985; Matchen *et al.*, 2011; NPS GRI program, 2012). The Princeton Sandstone is overlain by the Pride Shale Member of the Bluestone Formation (Englund and Thomas, 1985;

Matchen *et al.*, 2011; NPS GRI program, 2012). The Pride Shale Member is overlain by the Glady Fork Sandstone, which is also calcite-cemented, conglomeritic sandstone (Englund and Thomas, 1985; Matchen *et al.*, 2011; NPS GRI program, 2012).

New River originates in the Blue Ridge Mountains near Blowing Rock, North Carolina, at elevations in excess of 1220 m (4000 ft). The Blue Ridge is underlain by Cambrian metasedimentary rocks and Grenvillian (middle Proterozoic) basement gneisses (Bartholomew and Mills, 1991). In Giles County, Virginia, between the McCoy-Eggleston and Narrows-Rich Creek water gaps, New River trends north-northwest as it meanders across the structural fabric of the broadly folded and thrust-faulted portion of the Valley and Ridge physiographic province (Bartholomew and Mills, 1991; Mills and Wagner, 1985). New River Valley alternates between water gaps and wide valleys through this section due to the varying resistance of the sedimentary rocks (Fridley, 1950; Mills and Wagner, 1985). New River flows west as it follows the axis of the overturned Glen Lyn syncline, which is the western structural front of the Valley and Ridge province (Bartholomew and Mills, 1991). The river then returns to its north-northwest trend in the NERI study area, and meanders in deeply incised valleys across the relatively flat-lying rocks of the Appalachian Plateaus of West Virginia until it joins Gauley River at Gauley Bridge, West Virginia (Bartholomew and Mills, 1991; Mills, 1990), in the Logan Plateau (Outerbridge, 1987), to form Kanawha River (Bartholomew and Mills, 1991).

In the NERI study area, resistant sandstone units and some mineable coal units are most important for this research because they give characteristic signatures to the landscape. The New River Formation is dominant, and the Pocahontas, Hinton, and Bluefield formations are also exposed (Olcott, 2011; McColloch *et al.*, 2013; NPS GRI, 2014; Mills, 1990). The New River Formation is a coal-bearing sequence of sandstone, siltstone, shale, and underclay (Englund and

Thomas, 1985). The sandstone beds are quartz-pebble conglomerate and quartzose sandstone (Englund and Thomas, 1985; Mills, 1990). The Fire Creek, Beckley, and Sewell coal beds are found in the New River Formation (Englund and Thomas, 1985; McColloch *et al.*, 2013; NPS GRI, 2014). These coal beds have been extensively mined within NERI (Englund and Thomas, 1985). The Nuttall Sandstone Member in the upper New River Formation in NERI is generally informally divided into upper and lower members (McColloch *et al.*, 2013; NPS GRI, 2014). The upper member tends to be the cap rock in the northern portion of NERI (McColloch *et al.*, 2013; NPS GRI, 2014), where the lower member is an excellent cliff-former (Olcott, 2011). The resistant New River formation also causes the valley to narrow in this area (Mills, 1990). Upstream, farther south, the Raleigh Sandstone member in the lower New River Formation serves as a cap rock (McColloch *et al.*, 2013; NPS GRI, 2014) and substantial cliff-former (Olcott, 2011). The Pocahontas Formation is a coal-bearing sandstone with lesser amounts of siltstone and shale (Englund and Thomas, 1985). Pocahontas coal beds, particularly the Pocahontas no. 3 coal bed, are associated with the major anthropogenic features of the Pocahontas Formation in NERI, because of mining (Englund and Thomas, 1985).

LiDAR DEM Data

United States Army Corps of Engineers LiDAR DEM

A LiDAR dataset covering the New River and Kanawha River valleys from Bluestone Dam to Point Pleasant was acquired by contractors to the US Army Corps of Engineers (USCOE) as part of a Bluestone Dam safety assurance project in 2009 and provided for this thesis project. Lower Bluestone River was included in this dataset. Therefore, all of BLUE and 85% of NERI were covered during this acquisition of LiDAR data. The LiDAR bare-earth elevations were rasterized by the contractor, producing a DEM with 2 m x 2 m pixels (United States Army Corps of Engineers, 2009). The horizontal accuracy of the DEM is +/- 45.72 cm (United States Army Corps of Engineers, 2009). The vertical accuracy of the DEM is +/- 18.2 cm in areas that are within the boundaries of this project (United States Army Corps of Engineers, 2009).

<u>WVDEP Division of Mining and Reclamation LiDAR DEM</u>

A LiDAR dataset covering Babcock State Park within the NERI mapping boundary, which was not included in the USCOE DEM, was acquired by the West Virginia University Natural Resource Analysis Center (WVU NRAC) in 2011. A bare-earth point cloud dataset was acquired in .LAS file format from the West Virginia Department of Environmental Protection's (WVDEP) Division of Mining and Reclamation website. The average post spacing of the data was 1 m. The horizontal accuracy of these data was not reported in the metadata (WVU NRAC, 2011), however the vertical accuracy was estimated to be +/- 15 cm at a 95 percent confidence interval (WVU NRAC, 2011). The .LAS files were imported into ArcMap 10.2.2 where the 'Create LAS Dataset' tool within the' Data Management' toolbox was used to combine the .LAS files into a LAS dataset using a NAD83 coordinate system. The new LAS dataset was input into the 'LAS Dataset to Raster' tool within the 'Data Management' toolbox to create a raster DEM using elevation in the value field, triangulation as the interpolation type, natural neighbor as the interpolation method, no point thinning, and a 1 m pixel size.

Methods

Surficial geology units were first studied and described in the BLUE field area, using extensive field observations (Figure 9) and on-screen digitization of DEM computer visualizations at a 1:3,000 screen scale. BLUE was mapped first due to its smaller area and greater accessibility.

The units and descriptions from BLUE were adapted and modified to map landforms in NERI, using visual interpretation of the DEMs, and limited field confirmation.

Bluestone National Scenic River (BLUE)

LiDAR Processing

The U.S. Army Corps of Engineers LiDAR tiles within the BLUE National Scenic River and the 100 m buffered NPS boundary were mosaicked. The mosaicked raster dataset projection was transformed from 'NAD 1983 State Plane West Virginia South FIPS 4702 Feet' to 'NAD83 UTM Zone 17N'. The z-coordinates representing elevation were converted from feet to meters using the Raster Calculator in ArcMap 10.1.

A map of topographic slope (in degrees) was used as the basic dataset for interpretation of the DEM data. A slope map was chosen instead of a hillshade because the latter emphasizes aspect, which was not of relevance for the geomorphological classes of interest. The slope map was classified into 13 classes, using a natural breaks algorithm, and the resulting classes were displayed using a white to black gradational symbology (Figure 10). The number of slope classes was chosen by empirical comparison of a range of values, and selecting the number that appeared to provide the best representation of BLUE geomorphology.

Field Data Collection

Field data collection to identify the dominant landforms in BLUE began in July 2011 and completed by August 2012 (Figure 9). GPS points corresponding to a change in landform type or other features of interest were recorded with a handheld Garmin eTREX GPS device. A thorough description (dimensions, shape, material texture, etc.) and identification of the landform were recorded at each point. There were 367 data points collected at BLUE. The GPS points were then uploaded into ArcMap 10.1. The boundary of each landform was then manually digitized using the GPS points, the DEM and the field notes. These procedures are described in more detail below.

Mapping Phase

Base maps of the West Virginia Statewide Addressing and Mapping Board (SAMB) 2003 aerial imagery, overlain by mapped landforms and previous data points, were created for the Pipestem Resort State Park Region of BLUE. The boundaries of landforms were checked in the field, and the locations of the corrected boundaries were mapped using GPS and described along field transects. The data were uploaded into the ArcMap file, and the edges of the landforms were edited as needed.

Eleven surficial geology map units were identified in BLUE: floodplains, alluvial fans, fluvial channels, bouldery tributary deposits, terraces, landslides, colluvial fans, colluvial apron, colluvial mantle, colluvial veneer, and residuum (Table 1). Because of labor and time constraints, mappable units were required to be ≥30 m in length and width. It would have required longer than the time available for the project to map in more detail. All surficial geology units were delineated based on landforms and associated deposits and digitized at 1:3,000 scale on the LiDAR imagery in order to accurately depict the unit boundaries. Table 1 provides criteria used to define and map each surficial geology unit within BLUE.

The DEM imagery was visually interpreted based on image texture, slope steepness, and slope position. Areas displayed on the image with a smooth or uniform image texture were easily differentiated from image areas with varying texture. Steep areas were differentiated from flat areas using the slope map. A landform's slope position, in addition to its image texture and steepness, contribute to identification of its surficial geology classification.

Natural Resource Conservation Service (NRCS) soil survey data (Soil Survey Staff, 2011a and 2011b) were also used to aid the mapping of surficial geology. The NRCS soil data used included information about parent material and depth to bedrock, which helped to inform the location of surficial geology boundaries and the assignment of the class labels. All 11 landforms and surficial geology units within BLUE were manually digitized based on field data, soil survey data, and unit delineation criteria.

Floodplains are located in valley bottoms adjacent to rivers, and appear smooth and flat, with localized channelization.

Terraces are located at a slightly higher elevations in proximity to rivers, and appear smooth and flat.

Alluvial fans are located in valley bottoms at the mouth of tributaries, are fan-shaped and appear relatively smooth, generally with better-defined channels than floodplains.

Bouldery tributary deposits appear very rough in texture and are located in highly confined tributary bottoms.

Fluvial channels are incised in narrow valleys of short very high gradient streams.

Colluvial fans are generally located in footslopes below confined sediment sources, are fan-shaped, and steep to gently sloping.

Colluvial aprons are located in footslopes and appear smooth and gently sloping.

Colluvial veneers are located in the upper and middle slopes, are very steep, and exhibit a very rough texture with bedrock discontinuously to continuously apparent.

Colluvial mantles are located in the upper and middle slopes, are steeper than colluvial aprons yet typically not as steep as colluvial veneers, are rougher in image texture than colluvial aprons, but not as rough as colluvial veneers, and are locally dissected with gullies.

Landslides are located in the upper, middle, and footslopes, are rough or grainy in texture, and may have lobate toes.

Residuum is located on generally flat to gently sloping uplands, and appears smooth in texture.

New River National Scenic River (NERI)

LiDAR Processing

The USCOE and WVDEP NERI LiDAR DEM data were mosaicked to create 7.5' quadrangle images, and converted to a UTM projection, following the methods used for the BLUE area. DEMs were created for Beckwith, Fayetteville, Thurmond, Prince, Meadow Creek, and Hinton USGS 1:24,000 quadrangles, as well as a single mosaic for Babcock State Park. Once the USCOE and WVDEP LiDAR DEMs were created, the methodology for processing and mapping were the same. Degree slope maps were created, also following the approach used for the BLUE area. However, for NERI, 21 classes were chosen for the slope map, compared to only 13 in BLUE, because the topography of NERI is steeper and has more vertical relief. In addition, hillshades were created for NERI to help further reveal and define the topography in very steep areas along New River gorge. Hillshades were created from the mosaicked raster files with solar azimuths of 315° and 45° and a solar altitude of 45°. The parameters for the hillshades were chosen using a trial and error approach, in which a large number of hillshades were generated encompassing a wide range of values, and the resulting images compared. The particular values chosen were the values that in combination produced the most useful imagery for interpretation. The hillshades were displayed using a black to white stretched symbology.

Each quadrangle was viewed on ArcMap 10.1 by overlaying the slope maps with the 315° and 45° azimuth hillshades, with all the maps displayed at 50% transparency. This method facilitated the visualization of topography in low-relief areas, where small changes in relief are often not discernible with just one hillshade. The combination of two hillshades was found to be particularly useful in differentiating landforms such as colluvial mantle and residuum.

Final Mapping Phase

NERI surficial geology units were mapped based on the rules that were created when mapping BLUE. The 17 surficial geology map units identified on the LiDAR include all 11 units mapped in BLUE, in addition to six other map units: **disturbed lands, river channels, rock-floored floodplains, tributary deposits**, **blocky mantles and rock cities**. The surficial geology units were mapped at a 1:3,000 screen image scale on the LiDAR imagery. As in BLUE, mapped surficial geology units had to be ≥30 m in length and width. Table 1 provides definitions and mapping criteria for each landform within NERI and how they relate to landforms mapped in BLUE. NRCS soil survey data (Soil Survey Staff, 2011c) regarding parent material and depth to bedrock was used to aid surficial geology mapping. All surficial geology units within NERI were manually digitized based on visual interpretation of the LiDAR, NRCS soil survey data, and surficial geology unit definitions (Table 1).

A limited number of field excursions were made to assess the accuracy of the surficial geology mapping. Time in the field was maximized by focusing on areas that that had complex or unusual geomorphology, such as rock-floored floodplains and rock cities. There were 29 data points collected at NERI.

Disturbed lands are located in all slope positions, and are identified as being unusually smooth and typically include unnatural geometries such as steep highwalls and spoil slopes resembling small, exceptionally steep colluvial aprons.

River channels are the perennial river channels that are $\geq$ 30 m wide. They typically have a very smooth appearance due to LiDAR not penetrating the water surface.

Floodplains are located in the valley bottom adjacent to rivers, and appear smooth and flat, with localized channelization.

Rock-floored floodplains are located in the valley bottom adjacent to rivers, and are underlain by bare bedrock or exceptionally thin alluvium over bedrock. They appear rough and marked with potholes.

Terraces are located at a slightly higher elevation in proximity to rivers, and appear smooth and relatively flat.

Alluvial fans are located in the valley bottom at the mouth of tributaries, are fan-shaped and appear relatively smooth, generally with more well defined channels than floodplains.

Tributary deposits are irregular narrow bottomlands along steep tributary streams in confined valleys, typically entrenched by a channel with steep banks.

Bouldery tributary deposits appear very rough in texture and are located in steep confined tributary channels.

Fluvial channels are incised in narrow bottoms of very high gradient streams.

Colluvial fans are generally located in footslopes at the base of a confined source, are fan-shaped, and moderately to gently sloping.

Colluvial aprons are located in footslopes and appear smooth and gently sloping.

Colluvial veneers are located in the upper and middle slope, are very steep, and exhibit a very rough texture with apparent bedrock, locally obscured by patches of thick colluvium.

Colluvial mantles are located in the upper and middle slope, are steeper than colluvial aprons yet not as steep as colluvial veneers, and may be rougher in image texture than colluvial aprons, but not as rough as colluvial veneers. They are locally dissected by gullies.

Blocky mantles are colluvial mantle with numerous blocks projecting above the surface topography. Indicated on LiDAR by extreme surface roughness, blocky mantle reflects upslope occurrence of thick, highly resistant sandstones.

Landslides are located in the upper, middle, and footslopes, are rough or grainy in texture, and may have lobate toe slopes.

Rock cities are networks of large blocks separated by open passages, reflect lateral spreading of thick jointed sandstone from gentle upland slopes on to adjacent steep slopes.

Residuum is located on relatively flat uplands, and is generally flat to gently sloping and appears smooth in texture.

Results and Discussion

The surficial geology of BLUE is shown in Figure 11, upper NERI in Figure 5, middle NERI, including Babcock State Park, in Figure 6, and lower NERI in Figure 7. The total area of BLUE, NERI and the three NERI subsections are shown in Table 2. Table 3 shows the proportions of the study area covered by each surficial geology map unit.

Surficial geology units were analyzed in relation to the types of bedrock with which they were associated, which is discussed in detail in the following sections.

Disturbed Landforms

No large anthropogenic landforms were identified in BLUE, therefore, disturbed landforms were not mapped in that area. In contrast, disturbed landforms were mapped throughout NERI (Figure 12). The percentage of the landscape mapped as disturbed is highest in middle NERI and lowest in upper NERI (Table 3). In middle NERI, three main contributors caused anthropogenic disturbance: mining of the Sewell coal (McColloch *et al.*, 2013), mining of the Fire Creek Coal (McColloch *et al.*, 2013), and railroad and road construction (Table 4). Lower NERI anthropogenic disturbance is mainly due to railroads and roads, and some mining of the Sewell and Little Raleigh coals (Table 4) (McColloch *et al.*, 2013). Upper NERI has anthropogenic disturbance largely due to railroads and roads, residential development, and some mining of the Fire Creek and Beckley coals (Table 4) (McColloch *et al.*, 2013).

River Channels

The Bluestone River channel does not consistently meet the 30 m minimum width of the River Channel class criteria, and therefore was not mapped in BLUE. However, the river channel was mapped in NERI (Figure 13 and Table 3), where it was associated with the Bluefield and Hinton formations in Upper NERI, the Hinton and Bluestone formations in middle NERI, and the Pocahontas Formation and Raleigh Sandstone in Lower NERI (Table 5) (McColloch *et al.*, 2013).

Floodplains

The largest proportion of the landscape mapped as Floodplain was in BLUE, as shown in Table 3 and Figures 14 and 15. Floodplains were most extensive on the Hinton Formation in BLUE, middle NERI, and upper NERI (Table 6). The Bluefield formation also underlies a large portion of floodplain in Upper NERI (Table 6). The Upper Nuttall Sandstone made up a large portion of the narrow floodplain in Lower NERI.

Rock-floored Floodplains

Rock-floored floodplains (Figure 16) were mapped only in upper NERI at Sandstone Falls, where the Hinton Formation - Stony Gap Sandstone member crops out along New River (Table 7) (McColloch *et al.*, 2013). Although covering a very small surface area (0.03% of Upper NERI), National Park Service staff requested rock-floored floodplain be mapped separately because of the ecological significance of the Appalachian Riverside Flatrock Community (National Park Service, 2015) developed on this unit.

Terraces

Terraces were mapped in both BLUE (Figure 17) and NERI (Figure 18), but comprise a larger proportion of the landscape in BLUE (Table 3). Terraces were primarily associated with the Hinton Formation, except in lower NERI where 0.01 km^2 of terrace area was mapped on the Upper Nuttall Sandstone (Table 8) (McColloch *et al.*, 2013).

Alluvial Fans

Alluvial fans (Figures 19 and 20) were mapped in the valley bottoms at the mouths of some tributaries entering Bluestone River or New River. Alluvial fans were found most often in association with the Hinton Formation for BLUE, middle NERI, and upper NERI (Table 9). They were associated most commonly with the Pocahontas Formation and Pineville Sandstone in Lower NERI (Table 9). The development of alluvial fans was not necessarily related directly to bedrock units on which they were found, but rather to the bedrock units or anthropogenic disturbances. The Hinton and Pocahontas formations are common in valley bottoms in both BLUE and NERI.

Tributary Deposits

Tributary deposits were mapped only in middle and upper NERI (Figure 21). Most tributary deposits were found in Upper NERI, where they developed mostly on the Hinton Formation (Table 10) (McColloch *et al.*, 2013). In middle NERI, tributary deposits also were found on the Bluestone, Pocahontas, and New River formations (Table 10) (McColloch *et al.*, 2013), sandstone-rich units that yield resistant boulders.

Bouldery Tributary Deposits

Bouldery tributary deposits were mapped in BLUE (Figure 22) and NERI (Figure 23). Table 3 shows bouldery tributary deposits make up a larger proportion of the landscape in BLUE than in NERI. The bouldery tributary deposits in BLUE lie mostly on the Hinton Formation, with minor occurrences on the Bluestone Formation (Table 11) (McColloch *et al.*, 2013). Bouldery tributary deposits are more common in Middle and Upper NERI than in Lower NERI (Table 11). They were largely associated with the Hinton, Bluestone, Pocahontas, and New River formations, including the Raleigh Sandstone (Table 11).

Fluvial Channels

Fluvial channels were mapped at a higher percentage in BLUE and Lower NERI, as shown in Table 3 and Figures 24 and 25. Fluvial channels mostly were found on the Hinton Formation in all study areas except Lower NERI (Table 12) (McColloch *et al.*, 2013). The New River Formation was the dominant bedrock unit associated with fluvial channels in Lower NERI (Table 12) (McColloch *et al.*, 2013).

Colluvial Fans

Colluvial fans were mapped in BLUE (Figure 26) and NERI (Figure 27). Although colluvial fans are relatively rare, making up less than 1% of the landscape in both study areas, Table 3 shows that colluvial fans cover greater percentages of the landscape in BLUE and middle NERI. All colluvial fans in BLUE developed on the Hinton Formation (Table 13) (McColloch *et al.*, 2013). The colluvial fans in middle NERI developed mostly on the Bluestone and Pocahontas formations (Table 13) (McColloch *et al.*, 2013). Only two colluvial fans were found in Upper NERI, with both developed in the Hinton Formation (Table 13) (McColloch *et al.*, 2013).

Colluvial Aprons

Colluvial aprons were mapped in BLUE (Figure 28) and NERI (Figure 29). Colluvial aprons comprise a larger percentage of the landscape in BLUE than in NERI, as can be seen in Table 3. The colluvial aprons in BLUE largely were associated with the Hinton Formation with minor occurrences with the Bluestone Formation (Table 14) (McColloch *et al.*, 2013). In lower NERI the colluvial aprons were associated with the Pocahontas and New River formations, including the Raleigh Sandstone (Table 14) (McColloch *et al.*, 2013). In middle NERI, colluvial aprons were found to occur largely in association with the Hinton, Bluestone, Pocahontas formations, as well as with the Princeton Sandstone (Table 14) (McColloch *et al.*, 2013). Most colluvial aprons were associated with the Hinton Formation in Upper NERI (Table 14) (McColloch *et al.*, 2013).

Colluvial Veneers

Colluvial veneers were mapped in BLUE (Figure 30) and NERI (Figure 31). Colluvial veneers were the most widespread surficial geology unit in BLUE (Table 3), making up over 50% of the study area. Colluvial veneers were also the dominant surficial geology unit in lower NERI, and the secondmost dominant unit in middle and upper NERI (Table 3). Most colluvial veneers were associated with the Hinton formation in BLUE and Upper NERI, the New River Formation in Lower NERI, and the Pocahontas, Bluestone, and New River formations in middle NERI (Table 15) (McColloch *et al.*, 2013).

Colluvial Mantles

Colluvial mantles were mapped in BLUE (Figure 32) and NERI (Figure 33). Table 3 shows that colluvial mantle is the most widespread surficial geology unit in middle and upper NERI, while being the second most dominant surficial geology unit in BLUE and lower NERI. The colluvial mantles in BLUE are associated with the Hinton Formation (Table 16). Colluvial mantles in lower NERI are mainly associated with the Upper Nuttall Sandstone (Table 16) (McColloch *et al.*, 2013). Colluvial mantles in middle NERI are mainly associated with the New River Formation, including the Raleigh Sandstone, and the Pocahontas Formation (Table 16) (McColloch *et al.*, 2013). Colluvial mantles in upper NERI are largely associated with the Hinton and Bluestone Formations (McColloch *et al.*, 2013).

Blocky Mantles

Blocky mantles (Figure 34) occurred most commonly in lower NERI (Table 3) in areas underlain by thick-bedded resistant sandstones of the New River Formation, particularly the Upper Nuttall Sandstone (Table 17) (McColloch *et al.*, 2013). Blocky mantles were associated with the New River Formation, including Raleigh Sandstone in Middle NERI (Table 17) (McColloch *et al.*, 2013). In upper NERI, blocky mantles were associated with the Hinton Formation (Table 17) (McColloch *et al.*, 2013).

Landslides

Landslides were mapped throughout BLUE (Figure 35) and NERI (Figure 36). Landslides are more common in middle NERI than any of the other study areas (Table 3). This result is partly due to the high density of anthropogenic disturbances relating to the mining of the Sewell coal in middle NERI (Yates and Kite, 2013), as well as the steeper walls of the gorge due to dominance of the lower Nuttall Sandstone as a cliff-former (Olcott, 2011; Mills, 1990). There are a number of rapids in this area of NERI that are related to the constricted and altered flow of the New River due to mass-movement deposits of the New River formation (Mills, 1990; Moore, 1999). There are three notable landslide complexes in middle NERI: the 2001 Elverton landslide (Figures 37 and 38), the Mann's Creek landslide (Figures 39 and 40), and the Rush Run Mine landslide complex (Figure 41). The Elverton and Mann's Creek landslides are associated with disturbed landforms created by mining of Sewell coal (McColloch *et al.*, 2013). Most of the Rush Run Mine landslide complex is associated with disturbance created by the mining of Fire Creek coal (McColloch *et al.*, 2013); however, the westernmost portion on this landslide (Figure 41) is associated with disturbed landforms created by mining of both Sewell and the Fire Creek coals (McColloch *et al.*, 2013). All of these coal beds are within the New River Formation undifferentiated unit (Table 18). There is also a high occurrence of landslides within the outcrop belt of the Bluestone Formation, which contains the Pride Shale member: one of the most notable shale beds within the study areas (Table 18) (Englund and Thomas, 1985; Matchen *et al.*, 2011; McColloch *et al.*, 2013; NPS GRI program, 2012). Landslides in BLUE and Upper NERI typically overlie the Hinton Formation (Table 18) (McColloch *et al.*, 2013).

Rock Cities

Rock cities (Figure 42) only occur in upper NERI (Table 3), almost entirely within the outcrop belt of Raleigh Sandstone (Table 19) (McColloch *et al.*, 2013). One small rock city within the outcrop belt of the Pineville Sandstone (Table 19) (McColloch *et al.*, 2013).

Residuum

Residuum was mapped in BLUE (Figure 43) and NERI (Figure 44). The residuum in BLUE is most commonly associated with the Bluestone Formation (Table 20) (McColloch *et al.*, 2013). Residuum in lower NERI is almost exclusively associated with the Upper Nuttall Sandstone and the Kanawha Formation (Table 20) (McColloch *et al.*, 2013). Residuum in middle NERI is largely associated with the New River Formation, including the Raleigh Sandstone (Table 20) (McColloch *et al.*, 2013). Residuum in upper NERI is commonly associated with the Hinton Formation, Raleigh Sandstone, and Bluestone Formation (Table 20) (McColloch *et al.*, 2013).

Conclusions

This research demonstrated the value of LiDAR-based DEMs as a medium upon which to map surficial geology in the steeply incised landscape of Bluestone National Scenic River (BLUE) and New River Gorge National River (NERI). This approach reduces time and cost in the field by allowing the researcher to focus on areas of complex geomorphology, rather than areas where landforms can easily be mapped from LiDAR DEMs (Jones *et al.*, 2007). The use of LiDAR DEMs for mapping in this project resulted in only four field deployments providing sufficient data to produce the maps. Using DEMs to map surficial geology was also found to be an accurate method. More than 90% of BLUE was mapped in the lab using LiDAR DEMs and then checked in the field. All of NERI was mapped using LiDAR-based DEMs, and only the most unusual or complex geology, such as rock-floored floodplain and rock cities, had to be confirmed in the field.

Surficial geology mapping using LiDAR DEMs does have limitations in certain circumstances. Areas that are very bouldery, or covered in dense undergrowth vegetation, such as *Rhododendron*, may limit the accuracy of LiDAR-derived DEMs (Maxwell, 2010). In addition, because of the fixed scale of DEMs, the necessity to choose a minimum width for the mapped units, 30 m in the case of this thesis, may have eliminated small landform units that could be important for analysis of landscape evolution or ecosystem management.

In conclusion, LiDAR-based DEMs were found to be useful for understanding the dynamics between bedrock stratigraphy and landscape development. LiDAR DEMs were effective in reducing field work and identifying surficial geology landforms.

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Table 1. New River-Bluestone NPS Unit Surficial Geology Map Explanation (Kite and Yates, 2014).

NERI Surficial Geology Unit	**BLUE Surficial Geology Unit**	**Age**	**Description**
Disturbed	Not Mapped	Anthropocene	Wide variety of disturbed landforms, in which $\geq$ 30 percent of topography has been altered through excavation, mining, filling or other anthropogenic process. Includes mined lands from top of highwall to base of spoil pile, unusually wide or complex road or railroad grades, and unnaturally smooth surfaces. surficial materials vary greatly.
River Channel	Not Mapped	Active	Perennial river channels, $\geq$ 30 m wide. Coarse to extremely coarse bedload and course point bar deposits largely reflect geology of adjacent slopes. Banks in steep narrow canyons are commonly composed of boulder or block lag derived from very coarse colluvial diamictons.
Floodplain	Floodplain	Active, Late Holocene	Relatively flat river bottomland, episodically inundated by floods. Surface may be dissected by secondary stream channels active during high flows and floods. Includes some very rarely inundated low terraces. Composed of alluvium sediments ranging from silts and clays to boulders.
Rock-Floored Floodplain	Not Mapped		Relatively flat river bottomland, episodically inundated by floods. Includes some low terraces that are very rarely inundated. Underlain by bare bedrock or exceptionally thin alluvium over bedrock. Surface may be marked with potholes.
Alluvial fan	Alluvial Fan	Active, Holocene, Late Pleistocene	Gently sloping fan emanating from, and typically dissected by, one or two source tributary streams. Composed of alluvial sediments ranging from sand to boulders. Fans with steep source basins may include debris flow deposits. Varied soil profile development, reflecting complex age and genesis.
Tributary Deposit	Not mapped		Irregular narrow bottomlands along steep tributary streams in confined valleys, typically entrenched by a channel with steep banks. Composed primarily of relatively fine-grained silt to cobble deposits. Complex origins may include colluvial, debris flow, and alluvial deposition, modified by fluvial erosion.
Fluvial Channel	Fluvial Channel	Active, Holocene	Very steep highly entrenched > 30 m wide intermittent or perennial stream channels. Some may be debris flow tracks. Coarse to extremely coarse bed material may include bedrock outcrops and waterfalls. Banks in steep narrow canyons are commonly composed of boulder or block lag derived from very coarse colluvial diamictons.

NERI Surficial Geology Unit	BLUE Surficial Geology Unit	Age	Description
Terrace	Terraces	Holocene, Late Pleistocene	Relatively flat to gently sloping bottomland, seldom or never inundated by floods, and rarely displaying old inactive stream channels. Composed of alluvial sediments ranging from silts and clays to boulders, and commonly showing significant soil profile development. Locally mantled by thin colluvial deposits derived from adjacent slopes.
Landslide	Landslide	Anthropocene, Holocene, Late Pleistocene	Discrete slope failure, differentiated from adjacent landforms by distinct morphology, such as scarps, intact blocks, hummocks, or depositional toes. Slumps are most common landslide type. Lower portions of most landslides have been removed by mitigation along roadways and railroads, or erosion has adjacent to streams. Surficial materials vary greatly, reflecting source areas.
Colluvial Fan	Colluvial Fan	Holocene, Late Pleistocene	Fan- or cone-shaped landforms that can be traced to one or more confined sources, such as coves or hill-slope hollows. Composed primarily of colluvial diamicton, but may include debris flow deposits or tributary alluvium.
Colluvial Apron	Colluvial Apron	Pleistocene, Holocene	Footslope landforms with slope gradient generally decreasing downslope and no surface expression of underlying bedrock stratigraphy and structure. Composed of colluvial diamicton derived from unconfined sources. Underlying bedrock structure is not apparent because colluvium thickness exceeds 2 m.
Blocky Mantle	Not Mapped	Pleistocene, Holocene	Colluvial mantle with numerous blocks projecting above the surface topography. Indicated on LiDAR by extreme surface roughness, blocky mantle reflects *in situ* or upslope occurrence of thick, highly resistant sandstones.
Colluvial Mantle	Colluvial Mantle	Pleistocene, Holocene	Very steep to moderately steep slopes lacking surface expression of underlying bedrock stratigraphy and structure. Generally composed of thick (>2 m) colluvial diamictons reflecting upslope bedrock lithologies. Colluvium may include deposits deposited by sheet-flow and local fluvial processes.
Residuum	Residuum	Late Cenozoic	Low-relief uplands, typically rolling topography, lithologically controlled benches, or crests and shoulders of ridges and spurs. Composed of *in situ* or nearly *in situ* weathering products of varying textures and thicknesses, with properties inherited from underlying bedrock lithologies. May include local colluvial deposits.

NERI Surficial Geology Unit	BLUE Surficial Geology Unit	Age	Description
Rock City	Not Mapped	Pleistocene, Holocene	In-situ weathering of fractured and jointed exposed bedrock in low-relief uplands resulting in heavy erosion along fractures and joints creating very steep or cliff-like entrenched areas within the bedrock.

Table 2. The areas of the study areas.

Study Area	Area (km^2)
BLUE	22.1488
Lower NERI	29.9368
Middle NERI	180.6715
Upper NERI	111.5487
NERI	321.4997

Table 3. Percentages of BLUE, NERI, and NERI subareas. covered by surficial geology map units.

Surficial Geology Unit	BLUE	NERI	Lower NERI	Middle NERI	Upper NERI
Alluvial Fan	0.96%	0.40%	0.24%	0.46%	0.35%
Blocky Mantle	-	1.00%	7.27%	0.56%	0.03%
Bouldery Tributary Deposit	2.56%	0.75%	0.41%	0.90%	0.59%
Colluvial Apron	10.43%	7.67%	6.37%	8.24%	7.04%
Colluvial Fan	0.24%	0.11%	-	0.20%	0.01%
Colluvial Mantle	8.71%	32.17%	23.47%	31.96%	34.65%
Colluvial Veneer	53.44%	26.49%	24.87%	26.68%	26.45%
Disturbed	-	7.78%	7.18%	9.13%	5.70%
Floodplain	4.02%	1.19%	0.56%	1.15%	1.43%
Fluvial Channel	0.63%	0.17%	0.47%	0.14%	0.14%
Landslide	0.88%	0.85%	0.99%	1.22%	0.22%
Residuum	11.21%	16.04%	22.60%	15.52%	15.04%
River Channel	-	4.19%	5.51%	3.54%	4.88%
Rock City	-	0.01%	-	-	0.03%
Rock Floored Floodplain	-	0.08%	-	-	0.23%
Terrace	3.65%	0.46%	0.05%	0.30%	0.83%
Tributary Deposit	-	0.83%	-	0.02%	2.37%

Table 4. Disturbed areas in BLUE and NERI subareas and associated bedrock units.

Study Area	Surficial Geology Unit	Bedrock Unit	Total Area (km^2)
BLUE	**Disturbed**	-	-
Lower NERI	**Disturbed**	Pocahontas Formation	0.81
		New River Formation Undifferentiated	0.39
		Raleigh Sandstone	0.28
		Upper Nuttall Sandstone	0.27
		Pineville Sandstone	0.26
		Kanawha Formation	0.14
		Bluestone Formation	0.01
		Lower Nuttall Sandstone	0.00
		Total over all bedrock units	**2.15**
Middle NERI	**Disturbed**	New River Formation Undifferentiated	8.60
		Hinton Formation	2.91
		Raleigh Sandstone	1.77
		Bluestone Formation	1.35
		Pineville Sandstone	0.75
		Princeton Sandstone	0.73
		Pocahontas Formation	0.37
		Lower Nuttall Sandstone	0.01
		Total over all bedrock units	**16.49**
Upper NERI	**Disturbed**	Hinton Formation	4.02
		New River Formation Undifferentiated	1.60
		Bluefield Formation	0.36
		Bluestone Formation	0.17
		Princeton Sandstone	0.13
		Pocahontas Formation	0.07
		Pineville Sandstone	0.01
		Raleigh Sandstone	0.00
		Total over all bedrock units	**6.36**

Table 5. River channels in NERI subareas and associated bedrock units.

Study Area	Surficial Geology Unit	Bedrock Unit	Total Area (km^2)
BLUE	**River Channel**	-	-
Lower NERI	**River Channel**	Pocahontas Formation	0.62
		Raleigh Sandstone	0.52
		Pineville Sandstone	0.27
		New River Formation Undifferentiated	0.23
		Bluestone Formation	0.01
		Total over all bedrock units	**1.65**
Middle NERI	**River Channel**	Hinton Formation	4.43
		Bluestone Formation	1.00
		Princeton Sandstone	0.88
		Raleigh Sandstone	0.08
		New River Formation Undifferentiated	0.00
		Pocahontas Formation	0.00
		Total over all bedrock units	**6.39**
Upper NERI	**River Channel**	Bluefield Formation	3.09
		Hinton Formation	2.35
		Total over all bedrock units	**5.44**

Table 6. Floodplains in BLUE and NERI subareas and associated bedrock units.

Study Area	Surficial Geology Unit	Bedrock Unit	Total Area (km^2)
BLUE	**Floodplain**	Hinton Formation	0.89
		Total over all bedrock units	**0.89**
Lower NERI	**Floodplain**	Upper Nuttall Sandstone	0.15
		Pocahontas Formation	0.02
		Total over all bedrock units	**0.17**
Middle NERI	**Floodplain**	Hinton Formation	1.34
		Pocahontas Formation	0.36
		Princeton Sandstone	0.14
		Bluestone Formation	0.08
		Raleigh Sandstone	0.06
		Upper Nuttall Sandstone	0.06
		New River Formation Undifferentiated	0.02
		Pineville Sandstone	0.01
		Total over all bedrock units	**2.07**
Upper NERI	**Floodplain**	Hinton Formation	0.75
		Bluefield Formation	0.66
		New River Formation Undifferentiated	0.12
		Pineville Sandstone	0.03
		Bluestone Formation	0.03
		Princeton Sandstone	0.01
		Raleigh Sandstone	0.00
		Total over all bedrock units	**1.60**

Table 7. Rock-floored floodplains in BLUE and NERI subareas and associated bedrock units.

Study Area	Surficial Geology Unit	Bedrock Unit	Total Area (km^2)
BLUE	**Rock Floored Floodplain**	**-**	**-**
Lower NERI	**Rock Floored Floodplain**	**-**	**-**
Middle NERI	**Rock Floored Floodplain**	**-**	**-**
Upper NERI	**Rock Floored Floodplain**	Bluefield Formation	0.20
		Hinton Formation	0.06
		Total over all bedrock units	**0.26**

Table 8. Terraces in BLUE and NERI subareas and associated bedrock units.

Study Area	Surficial Geology Unit	Bedrock Unit	Total Area (km^2)
BLUE	**Terrace**	Hinton Formation	0.81
		Total over all bedrock units	**0.81**
Lower NERI	**Terrace**	Upper Nuttall Sandstone	0.01
		Total over all bedrock units	**0.01**
Middle NERI	**Terrace**	Hinton Formation	0.46
		Bluestone Formation	0.05
		Pocahontas Formation	0.01
		Pineville Sandstone	0.01
		New River Formation Undifferentiated	0.01
		Raleigh Sandstone	0.00
		Total over all bedrock units	**0.54**
Upper NERI	**Terrace**	Hinton Formation	0.57
		Bluefield Formation	0.30
		New River Formation Undifferentiated	0.03
		Bluestone Formation	0.01
		Pineville Sandstone	0.01
		Princeton Sandstone	0.00
		Total over all bedrock units	**0.93**

Table 9. Alluvial fans in BLUE and NERI subareas and associated bedrock units.

Study Area	Surficial Geology Unit	Bedrock Unit	Total Area (km^2)
BLUE	**Alluvial Fan**	Hinton Formation	0.21
		Total over all bedrock units	**0.21**
Lower NERI	**Alluvial Fan**	Pocahontas Formation	0.05
		Pineville Sandstone	0.01
		New River Formation Undifferentiated	0.01
		Upper Nuttall Sandstone	0.00
		Raleigh Sandstone	0.00
		Total over all bedrock units	**0.07**
Middle NERI	**Alluvial Fan**	Hinton Formation	0.53
		Bluestone Formation	0.18
		Princeton Sandstone	0.08
		New River Formation Undifferentiated	0.02
		Pineville Sandstone	0.01
		Raleigh Sandstone	0.01
		Pocahontas Formation	0.00
		Total over all bedrock units	**0.83**
Upper NERI	**Alluvial Fan**	Hinton Formation	0.35
		Bluefield Formation	0.04
		Total over all bedrock units	**0.39**

Table 10. Tributary deposits in NERI subareas and associated bedrock units.

Study Area	Surficial Geology Unit	Bedrock Unit	Total Area (km^2)
BLUE	**Tributary Deposit**	-	-
Lower NERI	**Tributary Deposit**	-	-
Middle NERI	**Tributary Deposit**	Bluestone Formation	0.01
		Pocahontas Formation	0.01
		Hinton Formation	0.01
		Princeton Sandstone	0.00
		Total over all bedrock units	**0.04**
Upper NERI	**Tributary Deposit**	Hinton Formation	1.79
		Bluestone Formation	0.39
		New River Formation Undifferentiated	0.21
		Pineville Sandstone	0.10
		Princeton Sandstone	0.06
		Pocahontas Formation	0.06
		Raleigh Sandstone	0.03
		Total over all bedrock units	**2.64**

Table 11. Bouldery tributary deposits in BLUE and NERI subareas and associated bedrock units.

Study Area	Surficial Geology Unit	Bedrock Unit	Total Area (km^2)
BLUE	**Bouldery Tributary Deposit**	Hinton Formation	0.50
		Bluestone Formation	0.06
		Total over all bedrock units	**0.57**
Lower NERI	**Bouldery Tributary Deposit**	New River Formation Undifferentiated	0.07
		Raleigh Sandstone	0.03
		Pocahontas Formation	0.01
		Lower Nuttall Sandstone	0.01
		Pineville Sandstone	0.01
		Upper Nuttall Sandstone	0.00
		Total over all bedrock units	**0.12**
Middle NERI	**Bouldery Tributary Deposit**	Bluestone Formation	0.52
		Pocahontas Formation	0.39
		New River Formation Undifferentiated	0.28
		Hinton Formation	0.14
		Raleigh Sandstone	0.12
		Pineville Sandstone	0.10
		Princeton Sandstone	0.09
		Total over all bedrock units	**1.62**
Upper NERI	**Bouldery Tributary Deposit**	Hinton Formation	0.40
		Bluestone Formation	0.23
		Princeton Sandstone	0.03
		Pocahontas Formation	0.00
		Total over all bedrock units	**0.66**

Table 12. Fluvial channels in BLUE and NERI subareas and associated bedrock units.

Study Area	Surficial Geology Unit	Bedrock Unit	Total Area (km^2)
BLUE	**Fluvial Channel**	Hinton Formation	0.14
		Total over all bedrock units	**0.14**
Lower NERI	**Fluvial Channel**	New River Formation Undifferentiated	0.05
		Upper Nuttall Sandstone	0.03
		Lower Nuttall Sandstone	0.02
		Pocahontas Formation	0.01
		Pineville Sandstone	0.01
		Raleigh Sandstone	0.01
		Total over all bedrock units	**0.14**
Middle NERI	**Fluvial Channel**	Hinton Formation	0.17
		Princeton Sandstone	0.04
		Bluestone Formation	0.02
		Pocahontas Formation	0.00
		New River Formation Undifferentiated	0.00
		Raleigh Sandstone	0.00
		Pineville Sandstone	0.00
		Total over all bedrock units	**0.24**
Upper NERI	**Fluvial Channel**	Hinton Formation	0.13
		Bluefield Formation	0.03
		Total over all bedrock units	**0.15**

Table 13. Colluvial fans in BLUE and NERI subareas and associated bedrock units.

Study Area	Surficial Geology Unit	Bedrock Unit	Total Area (km^2)
BLUE	**Colluvial Fan**	Hinton Formation	0.05
		Total over all bedrock units	**0.05**
Lower NERI	**Colluvial Fan**	-	-
Middle NERI	**Colluvial Fan**	Bluestone Formation	0.12
		Pocahontas Formation	0.08
		Hinton Formation	0.05
		Princeton Sandstone	0.04
		New River Formation Undifferentiated	0.04
		Pineville Sandstone	0.01
		Raleigh Sandstone	0.01
		Total over all bedrock units	**0.35**
Upper NERI	**Colluvial Fan**	Hinton Formation	0.01
		Total over all bedrock units	**0.01**

Table 14. Colluvial aprons in BLUE and NERI subareas and associated bedrock units.

Study Area	Surficial Geology Unit	Bedrock Unit	Total Area (km^2)
BLUE	**Colluvial Apron**	Hinton Formation	2.20
		Bluestone Formation	0.11
		Total over all bedrock units	**2.31**
Lower NERI	**Colluvial Apron**	Pocahontas Formation	0.66
		New River Formation Undifferentiated	0.62
		Raleigh Sandstone	0.48
		Pineville Sandstone	0.13
		Bluestone Formation	0.01
		Lower Nuttall Sandstone	0.00
		Total over all bedrock units	**1.91**
Middle NERI	**Colluvial Apron**	Hinton Formation	5.99
		Bluestone Formation	4.19
		Pocahontas Formation	2.21
		Princeton Sandstone	1.57
		New River Formation Undifferentiated	0.46
		Pineville Sandstone	0.34
		Raleigh Sandstone	0.13
		Total over all bedrock units	**14.89**
Upper NERI	**Colluvial Apron**	Hinton Formation	6.11
		New River Formation Undifferentiated	0.64
		Bluestone Formation	0.37
		Pineville Sandstone	0.22
		Pocahontas Formation	0.19
		Raleigh Sandstone	0.12
		Bluefield Formation	0.12
		Princeton Sandstone	0.10
		Total over all bedrock units	**7.85**

Table 15. Colluvial veneers in BLUE and NERI subareas and associated bedrock units.

Study Area	Surficial Geology Unit	Bedrock Unit	Total Area (km^2)
BLUE	**Colluvial Veneer**	Hinton Formation	10.86
		Bluestone Formation	0.98
		Total over all bedrock units	**11.84**
Lower NERI	**Colluvial Veneer**	New River Formation Undifferentiated	4.00
		Lower Nuttall Sandstone	1.06
		Raleigh Sandstone	0.94
		Upper Nuttall Sandstone	0.74
		Pocahontas Formation	0.33
		Pineville Sandstone	0.32
		Kanawha Formation	0.08
		Total over all bedrock units	**7.45**
Middle NERI	**Colluvial Veneer**	Pocahontas Formation	19.40
		Bluestone Formation	10.07
		New River Formation Undifferentiated	8.53
		Pineville Sandstone	3.26
		Raleigh Sandstone	2.87
		Hinton Formation	2.14
		Princeton Sandstone	1.77
		Lower Nuttall Sandstone	0.13
		Upper Nuttall Sandstone	0.05
		Total over all bedrock units	**48.21**
Upper NERI	**Colluvial Veneer**	Hinton Formation	20.59
		Bluestone Formation	4.55
		Pocahontas Formation	2.36
		Princeton Sandstone	1.47
		Pineville Sandstone	0.41
		Bluefield Formation	0.08
		New River Fornation Undifferentiated	0.04
		Total over all bedrock units	**29.50**

Table 16. Colluvial mantles in BLUE and NERI subareas and associated bedrock units.

Study Area	Surficial Geology Unit	Bedrock Unit	Total Area (km^2)
BLUE	**Colluvial Mantle**	Hinton Formation	1.74
		Bluestone Formation	0.18
		Total over all bedrock units	**1.93**
Lower NERI	**Colluvial Mantle**	Upper Nuttall Sandstone	5.40
		Kanawha Formation	0.78
		New River Formation Undifferentiated	0.55
		Lower Nuttall Sandstone	0.17
		Raleigh Sandstone	0.10
		Pineville Sandstone	0.02
		Pocahontas Formation	0.01
		Total over all bedrock units	**7.03**
Middle NERI	**Colluvial Mantle**	New River Formation Undifferentiated	17.97
		Raleigh Sandstone	15.91
		Pocahontas Formation	11.65
		Pineville Sandstone	4.49
		Bluestone Formation	3.49
		Hinton Formation	1.76
		Princeton Sandstone	1.24
		Upper Nuttall Sandstone	0.74
		Lower Nuttall Sandstone	0.48
		Kanawha Formation	0.02
		Total over all bedrock units	**57.74**
Upper NERI	**Colluvial Mantle**	Hinton Formation	13.15
		Bluestone Formation	9.62
		New River Formation Undifferentiated	4.61
		Raleigh Sandstone	3.69
		Pocahontas Formation	3.25
		Princeton Sandstone	2.24
		Pineville Sandstone	2.08
		Bluefield Formation	0.00
		Total over all bedrock units	**38.66**

Table 17. Blocky mantles in NERI subareas and associated bedrock units.

Study Area	Surficial Geology Unit	Bedrock Unit	Total Area (km^2)
BLUE	**Blocky Mantle**	-	-
Lower NERI	**Blocky Mantle**	Upper Nuttall Sandstone	1.42
		New River Formation Undifferentiated	0.32
		Lower Nuttall Sandstone	0.30
		Pocahontas Formation	0.03
		Pineville Sandstone	0.03
		Raleigh Sandstone	0.05
		Kanawha Formation	0.02
		Total over all bedrock units	**2.18**
Middle NERI	**Blocky Mantle**	New River Formation Undifferentiated	0.45
		Raleigh Sandstone	0.41
		Lower Nuttall Sandstone	0.06
		Upper Nuttall Sandstone	0.05
		Bluestone Formation	0.02
		Pocahontas Formation	0.02
		Pineville Sandstone	0.01
		Kanawha Formation	0.00
		Total over all bedrock units	**1.01**
Upper NERI	**Blocky Mantle**	Hinton Formation	0.04
		Total over all bedrock units	**0.04**

Table 18. Landslides in BLUE and NERI subareas and associated bedrock units.

Study Area	Surficial Geology Unit	Bedrock Unit	Total Area (km^2)
BLUE	**Landslide**	Hinton Formation	0.19
		Bluestone Formation	0.01
		Total over all bedrock units	**0.20**
Lower NERI	**Landslide**	New River Formation Undifferentiated	0.11
		Pocahontas Formation	0.07
		Pineville Sandstone	0.06
		Raleigh Sandstone	0.06
		Kanawha Formation	0.00
		Upper Nuttall Sandstone	0.00
		Lower Nuttall Sandstone	0.00
		Total over all bedrock units	**0.30**
Middle NERI	**Landslide**	Bluestone Formation	0.71
		Hinton Formation	0.49
		Pocahontas Formation	0.45
		Princeton Sandstone	0.25
		New River Formation Undifferentiated	0.15
		Pineville Sandstone	0.08
		Raleigh Sandstone	0.07
		Total over all bedrock units	**2.20**
Upper NERI	**Landslide**	Hinton Formation	0.23
		Bluestone Formation	0.01
		Princeton Sandstone	0.01
		Total over all bedrock units	**0.25**

Table 19. Rock cities in upper NERI and associated bedrock units.

Study Area	Surficial Geology Unit	Bedrock Unit	Total Area (km^2)
BLUE	**Rock City**	-	-
Lower NERI	**Rock City**	-	-
Middle NERI	**Rock City**	-	-
Upper NERI	**Rock City**	Raleigh Sandstone	0.03
		Pineville Sandstone	0.01
		Total over all bedrock units	**0.04**

Table 20. Residuum in BLUE and NERI subareas and associated bedrock units.

Study Area	Surficial Geology Unit	Bedrock Unit	Total Area (km^2)
BLUE	**Residuum**	Bluestone Formation	1.45
		Hinton Formation	1.03
		Total over all bedrock units	**2.48**
Lower NERI	**Residuum**	Upper Nuttall Sandstone	4.16
		Kanawha Formation	2.57
		Lower Nuttall Sandstone	0.03
		Total over all bedrock units	**6.77**
Middle NERI	**Residuum**	Raleigh Sandstone	13.89
		New River Formation Undifferentiated	8.59
		Pocahontas Formation	2.28
		Pineville Sandstone	1.73
		Upper Nuttall Sandstone	0.54
		Lower Nuttall Sandstone	0.46
		Bluestone Formation	0.23
		Princeton Sandstone	0.15
		Kanawha Formation	0.13
		Hinton Formation	0.03
		Total over all bedrock units	**28.03**
Upper NERI	**Residuum**	Hinton Formation	4.41
		Raleigh Sandstone	3.31
		Bluestone Formation	2.82
		New River Formation Undifferentiated	2.17
		Princeton Sandstone	1.70
		Pineville Sandstone	1.48
		Pocahontas Formation	0.88
		Total over all bedrock units	**16.78**

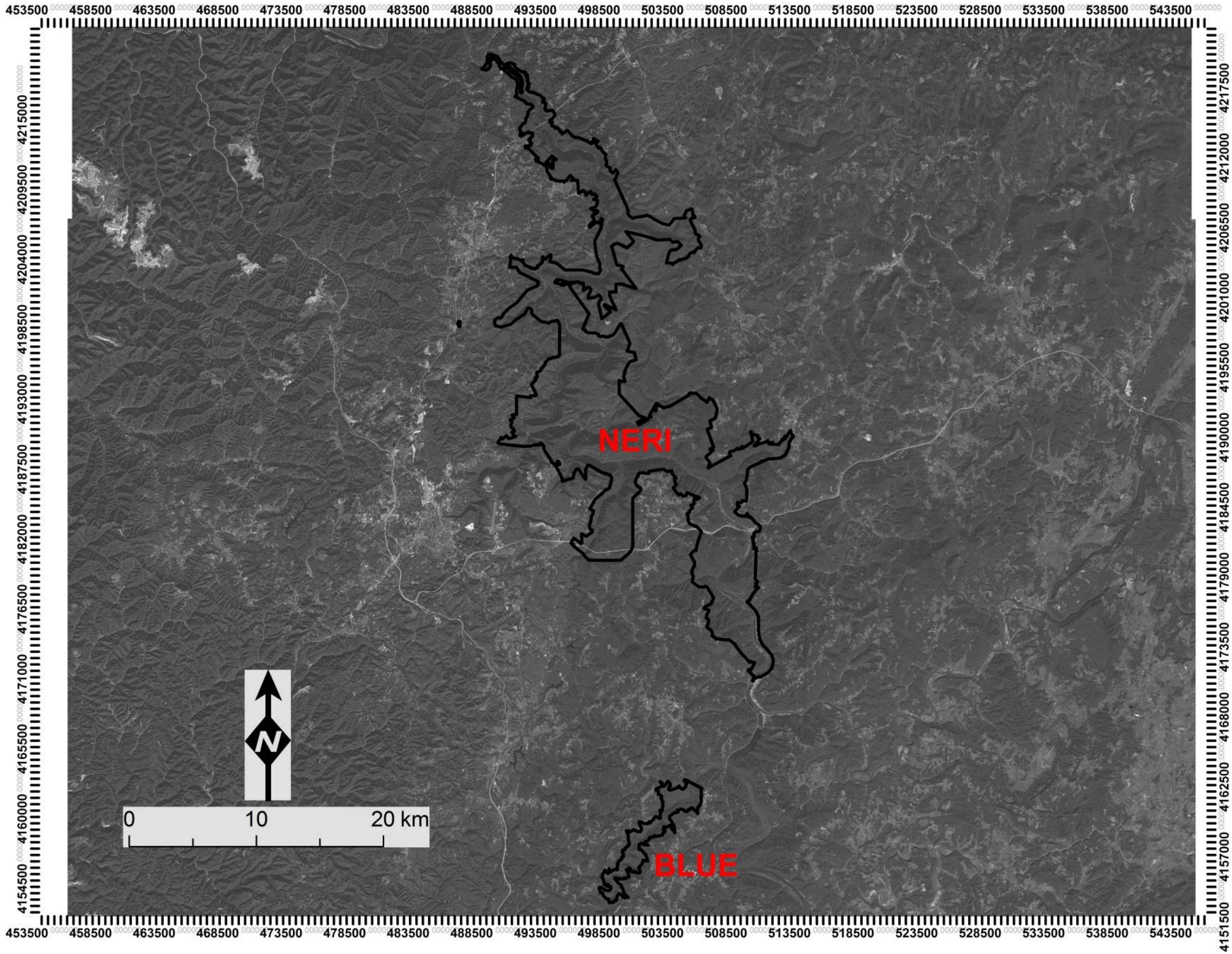

Figure 1. Bluestone National Scenic River (BLUE) and New River Gorge National River (NERI) study areas. SPOT 2001 base imagery.

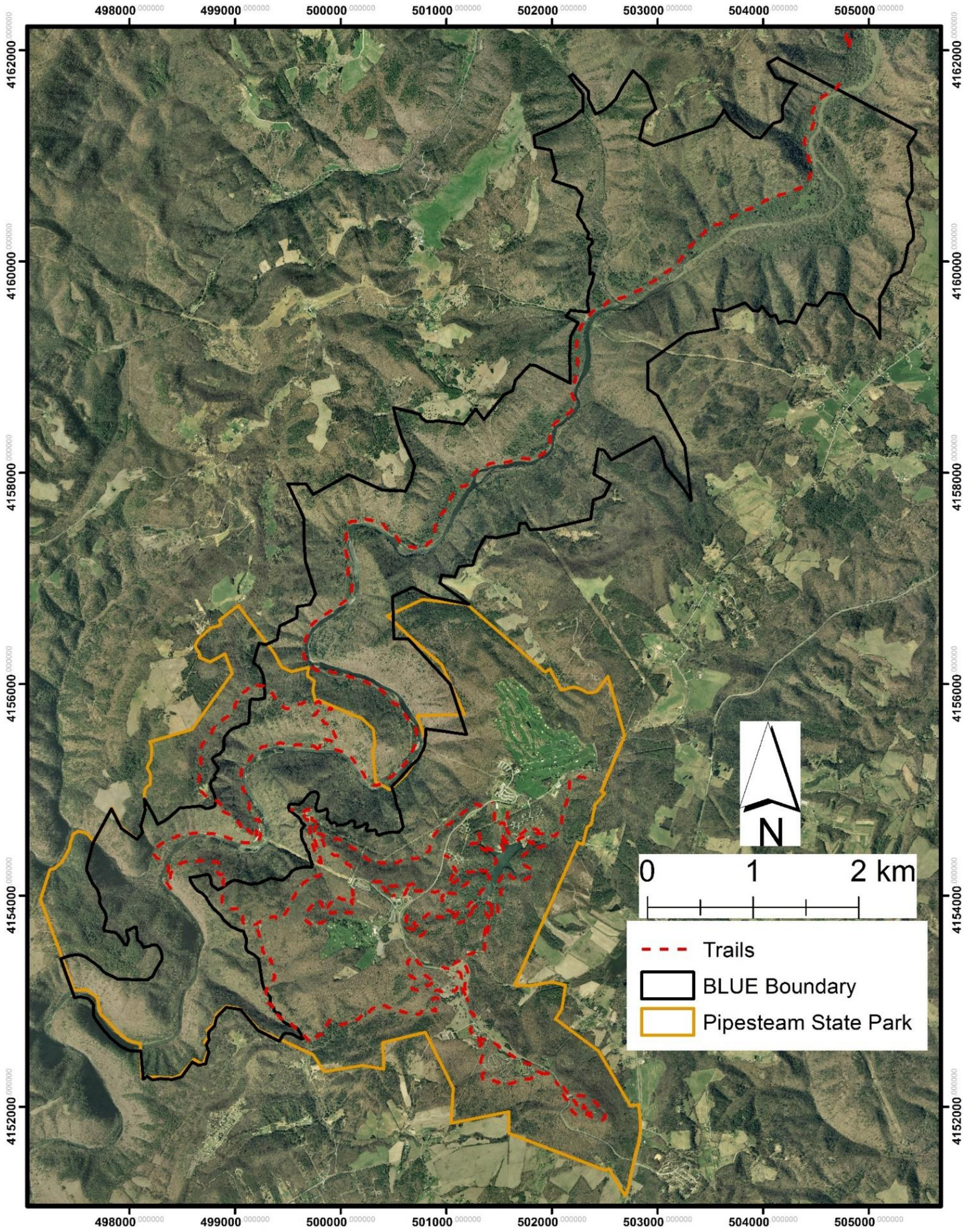

Figure 2. Bluestone National Scenic River (BLUE) study area, including the adjacent Pipestem State Park. West Virginia SAMB 2003 base imagery.

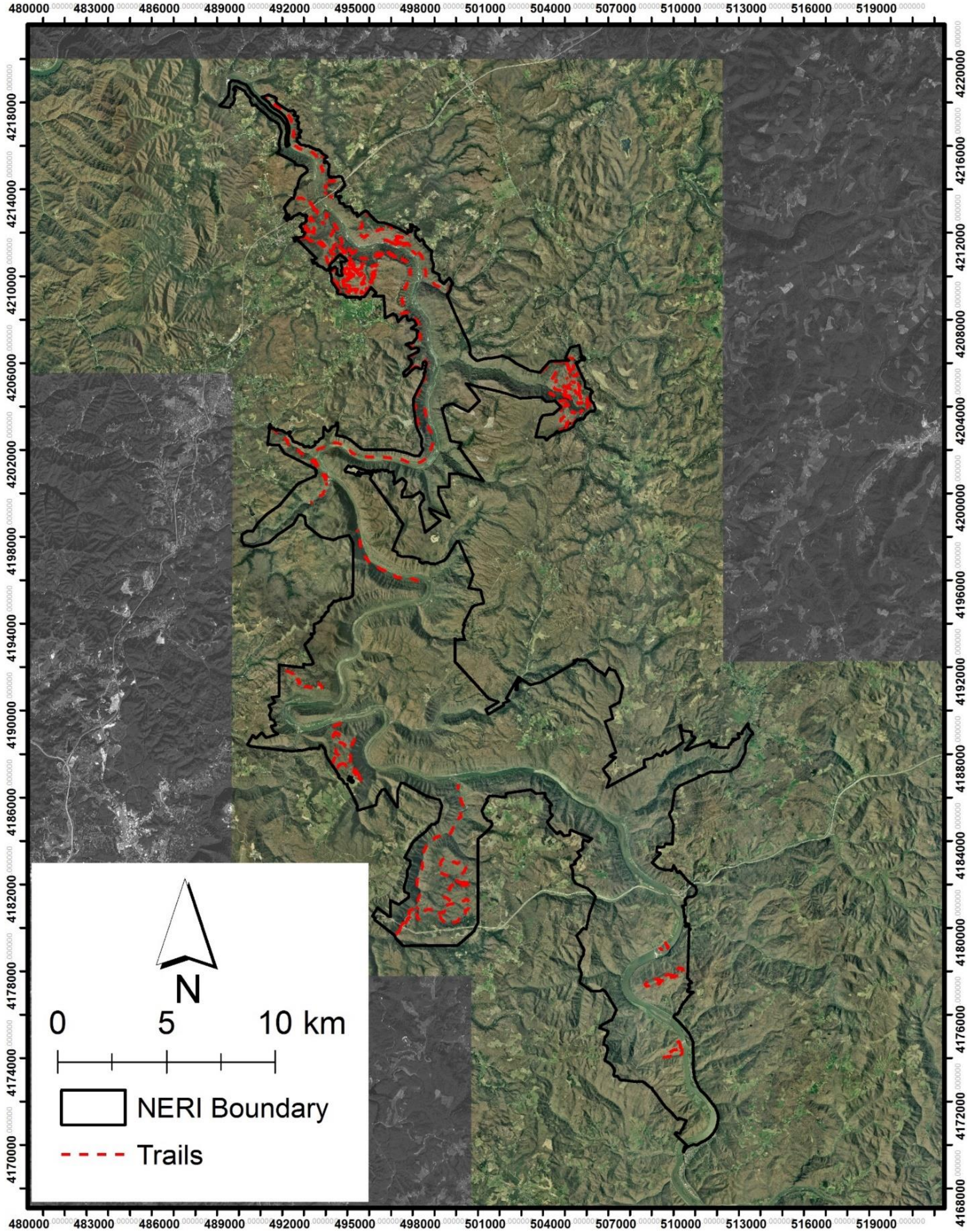

Figure 3. New River Gorge National Scenic River (NERI) study area, including the adjacent Babcock and Grandview State Parks, West Virginia SAMB 2003 and SPOT *2001* base imagery.

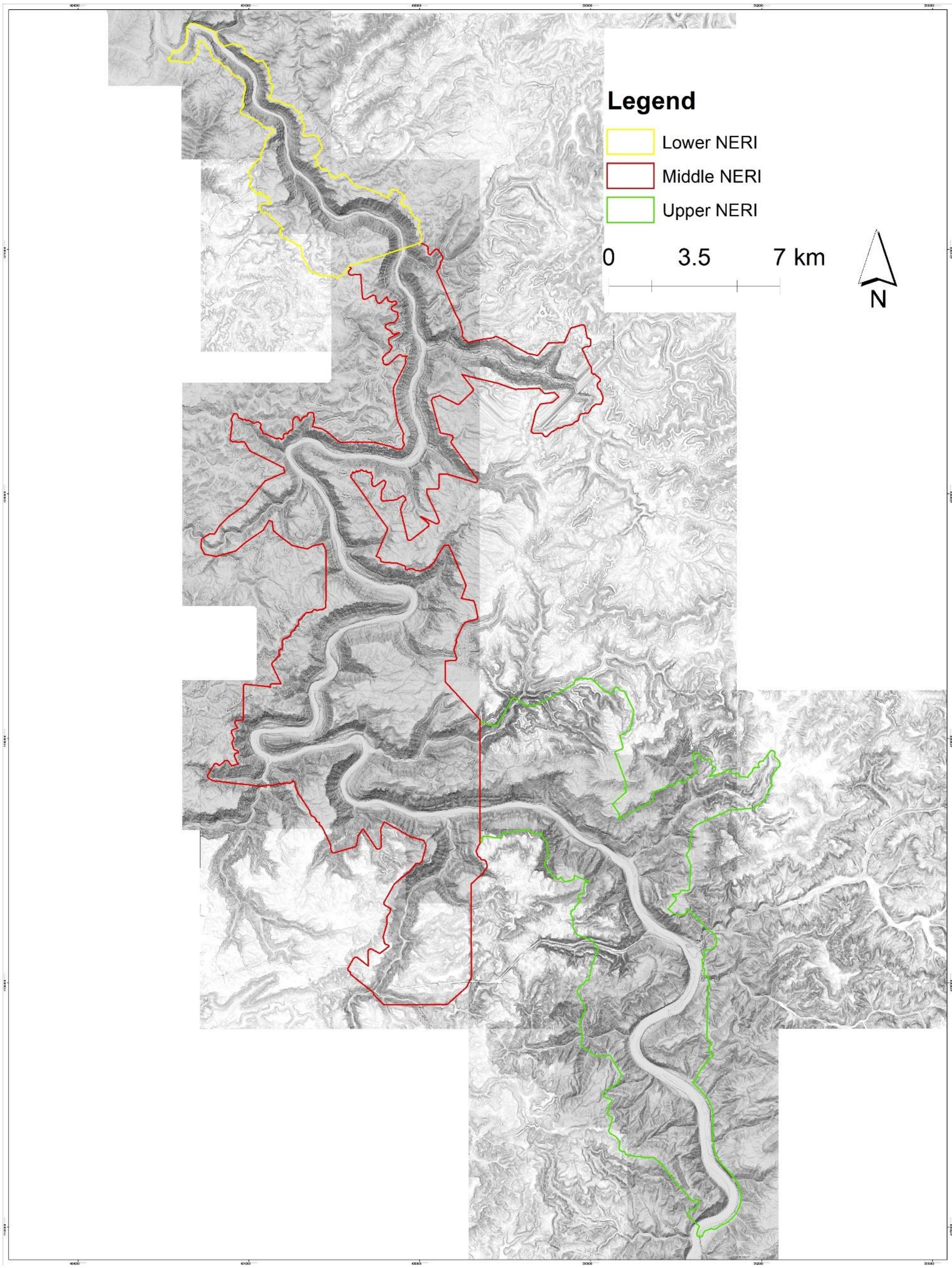

Figure 4. Boundaries of the upper, middle, and lower sections of NERI. Background imagery was created by overlaying the topographic slope maps with the 315° and 45° azimuth hillshades. All the maps are overlain and displayed at 50% transparency.

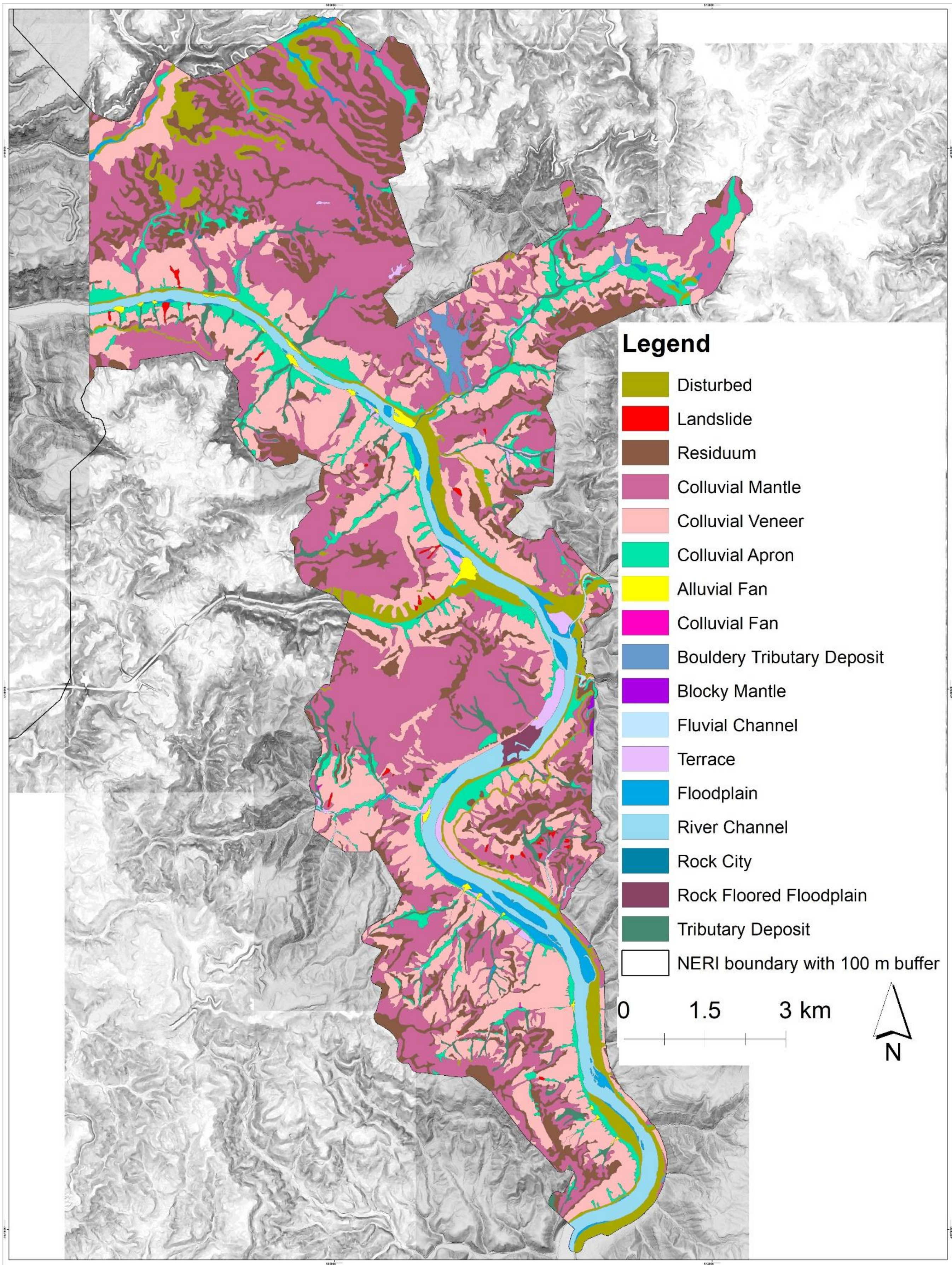

Figure 5. Surficial geology of the upper section of NERI.

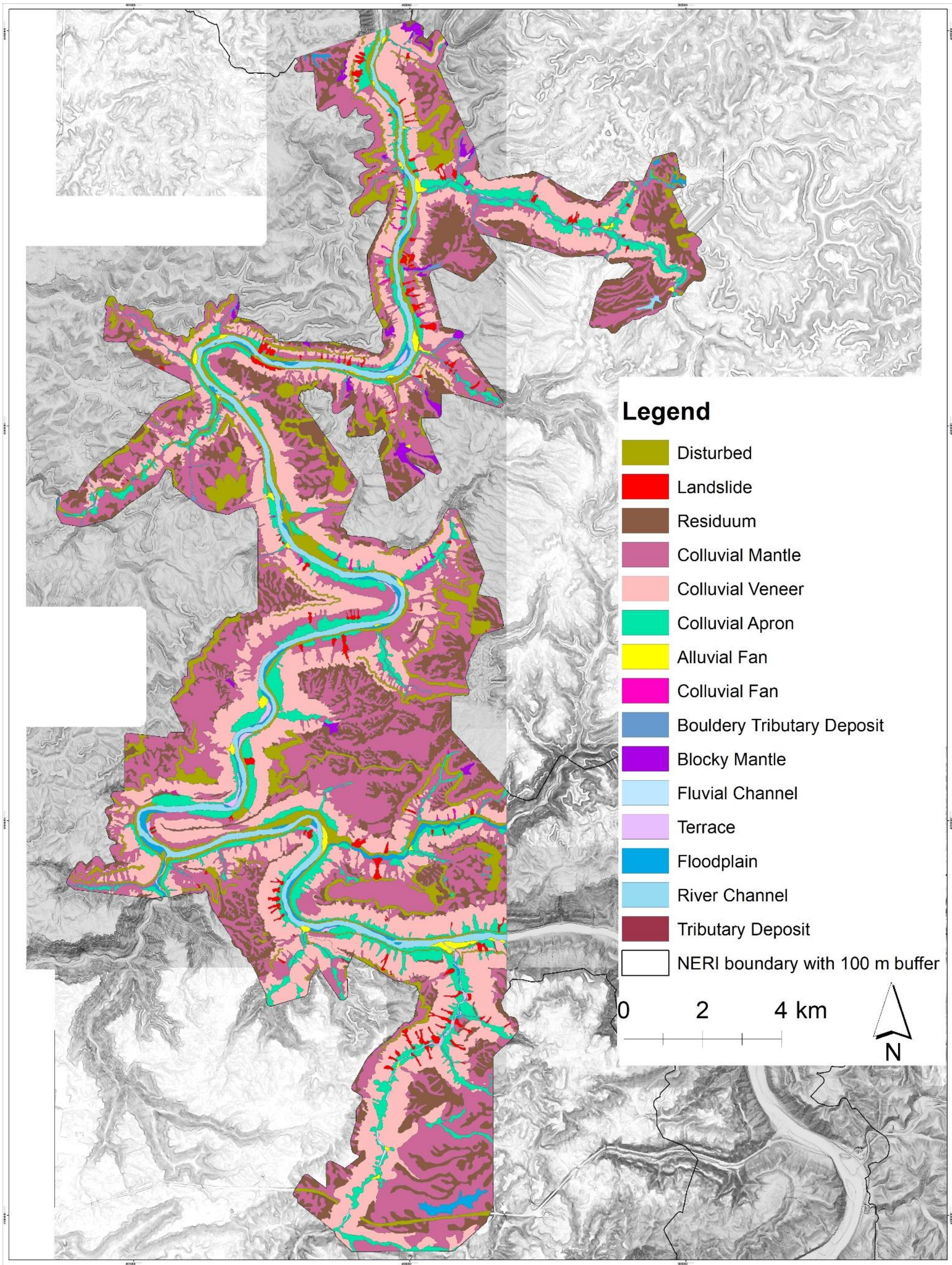

Figure 6. Surficial geology of the middle section of NERI, including Babcock State Park.

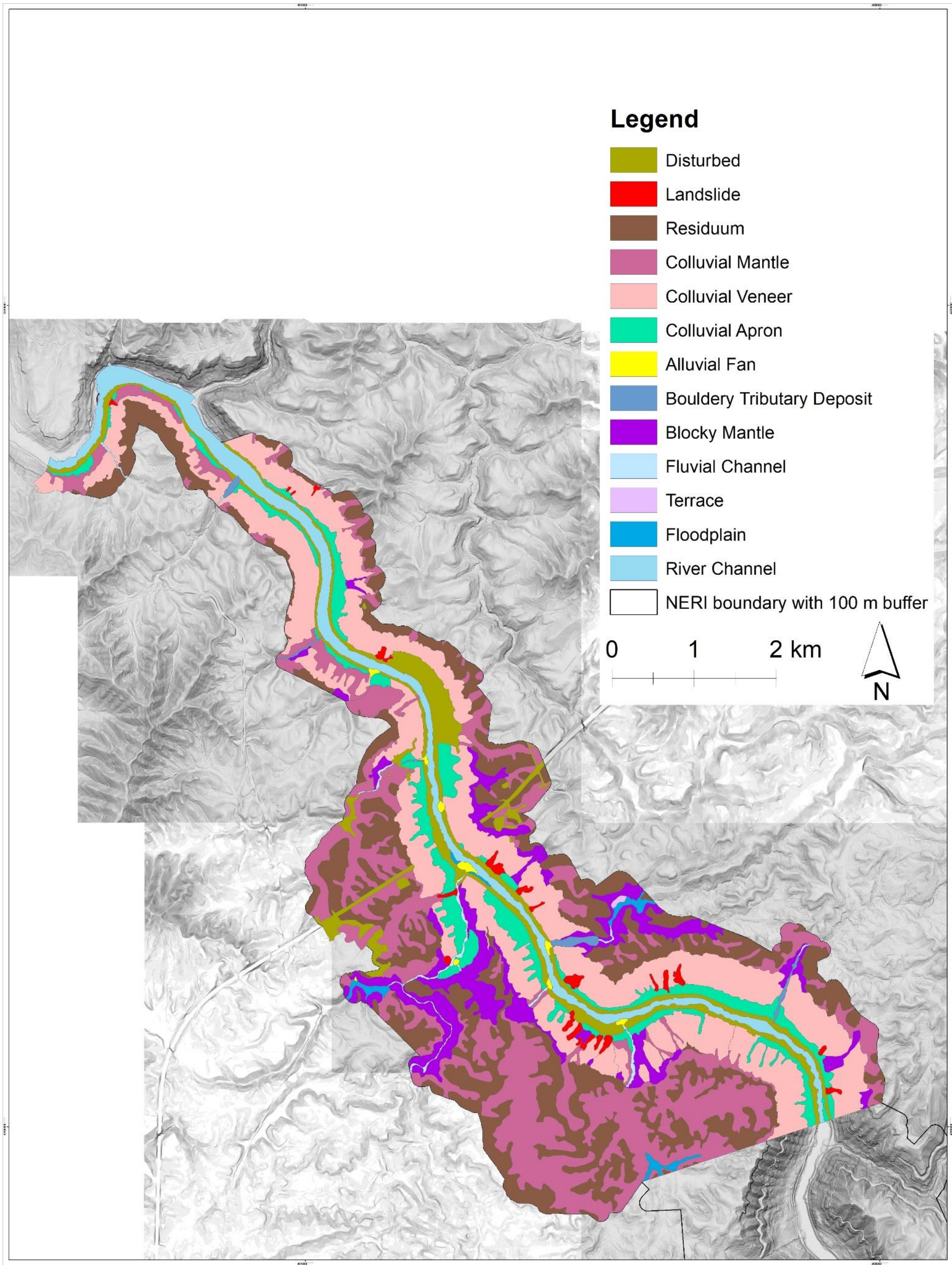

Figure 7. Surficial geology of the lower section of NERI.

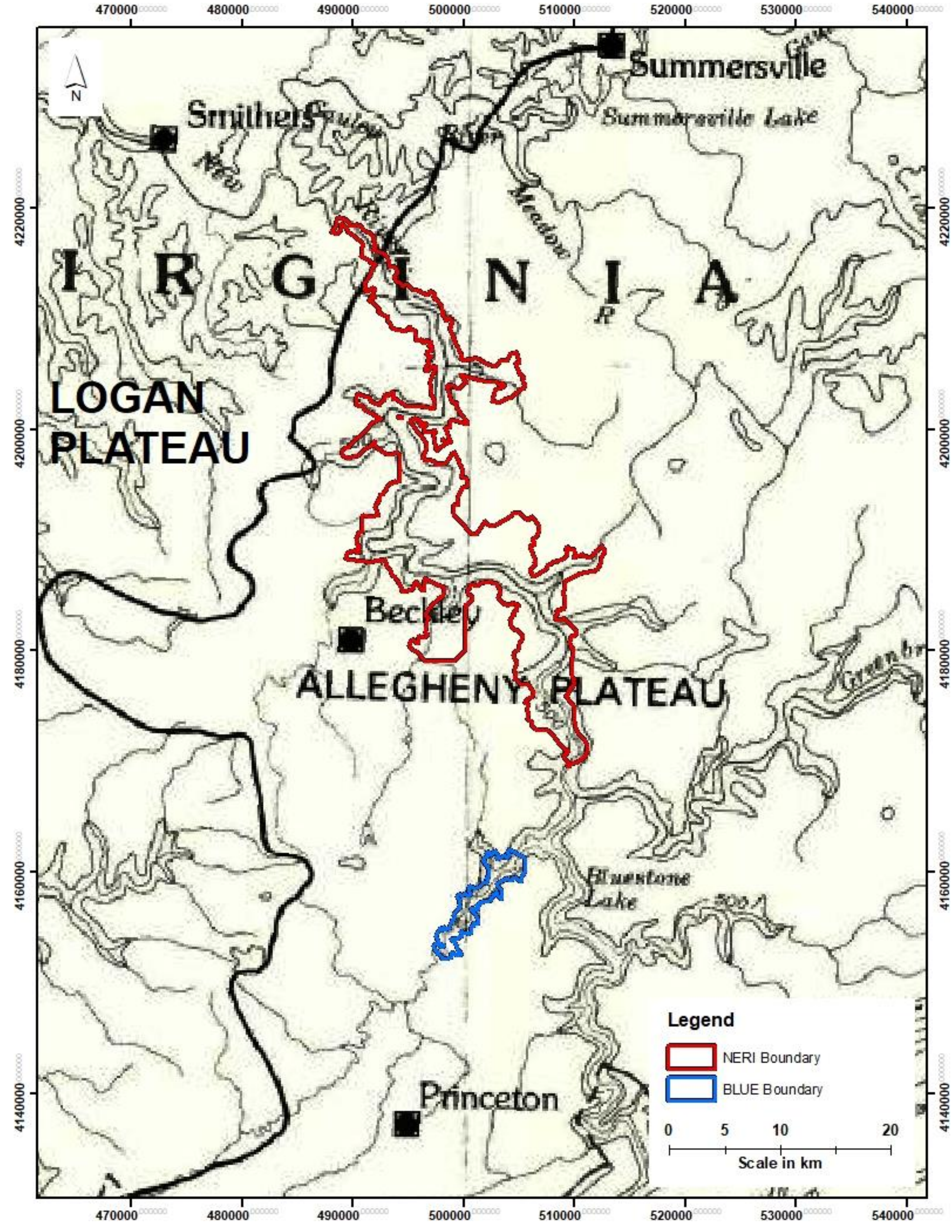

Figure 8. Logan and Allegheny plateaus from Outerbridge (1987, Plate 1), showing NERI and BLUE mapping areas.

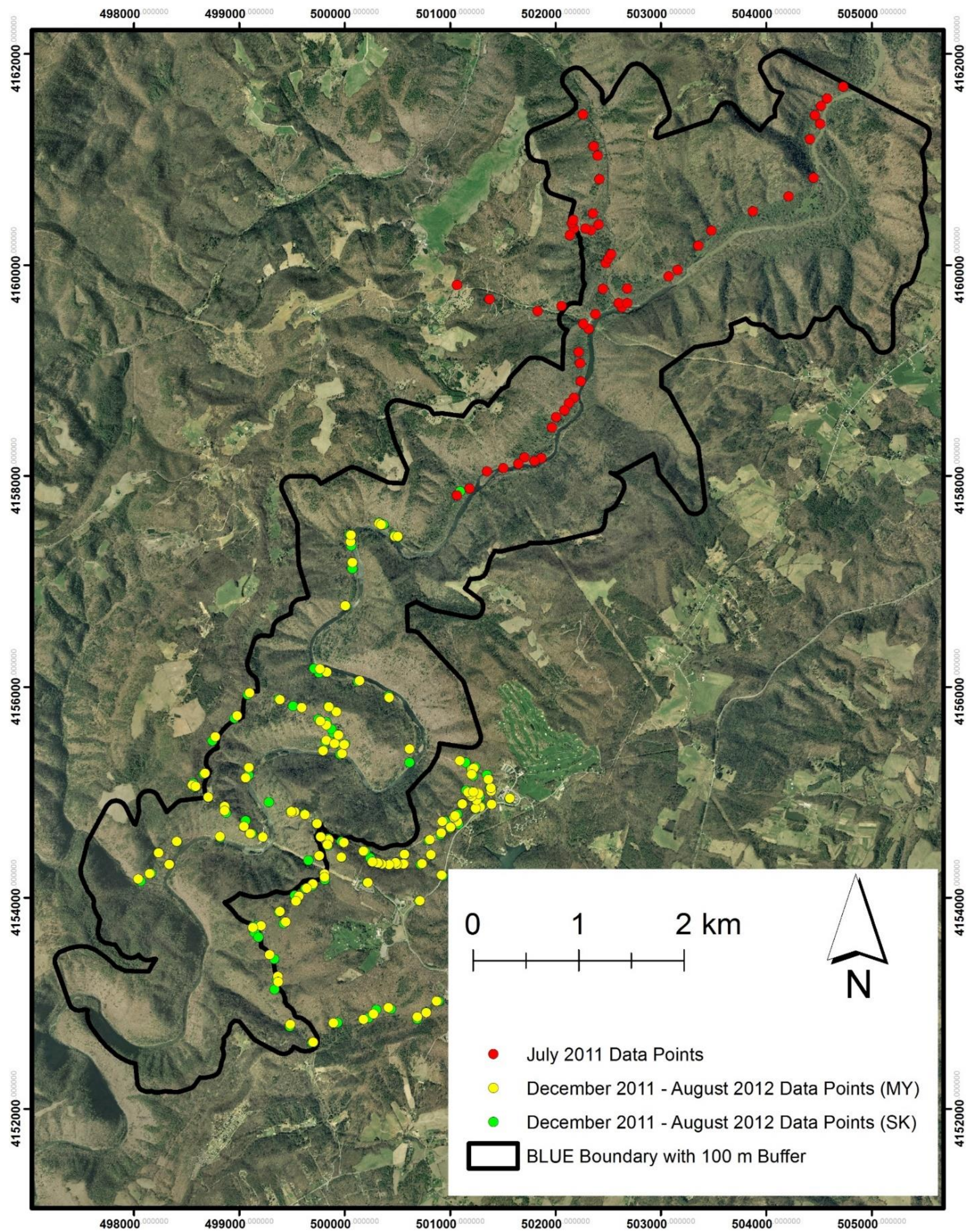

Figure 9. Locations of BLUE field data, including dates of collection. (MY refers to points collected by Marla Denicola; SK those collected by Steve Kite.)

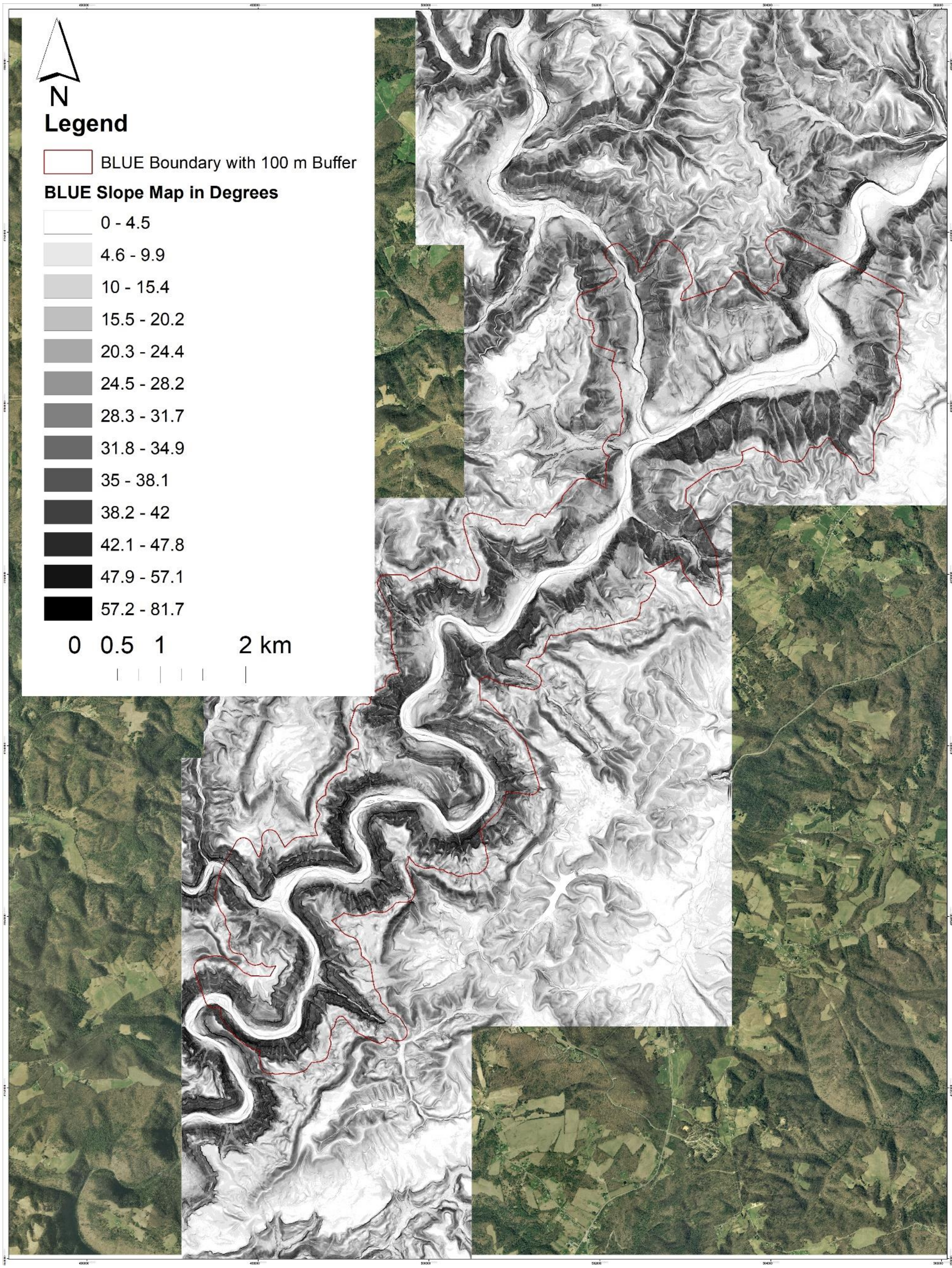

Figure 10. Slope map of BLUE study area using 13 slope classes. This figure and all subsequent BLUE figures are displayed using West Virginia SAMB 2003 base imagery overlain with this topographic slope map.

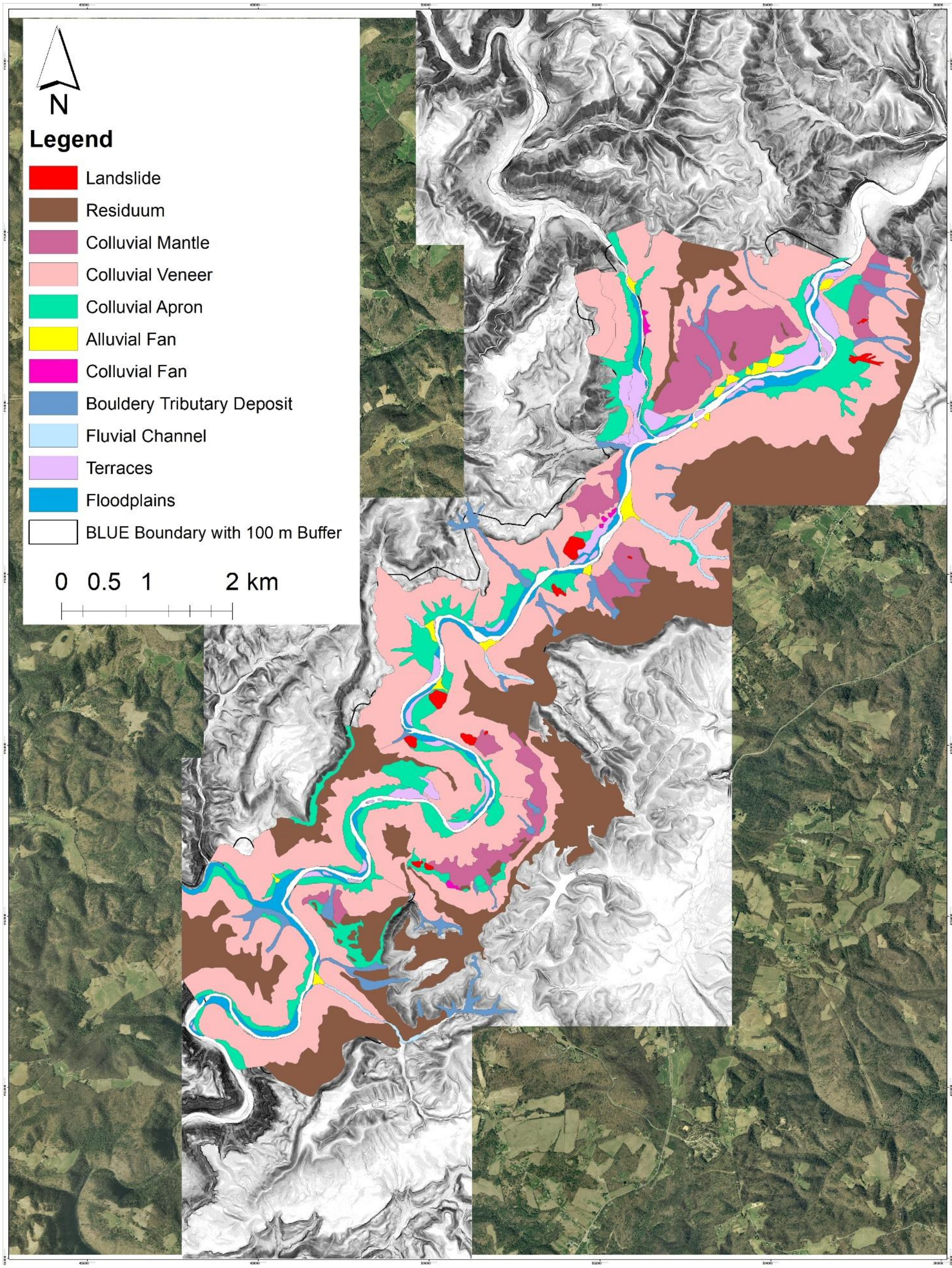

Figure 11. Surficial geology in BLUE.

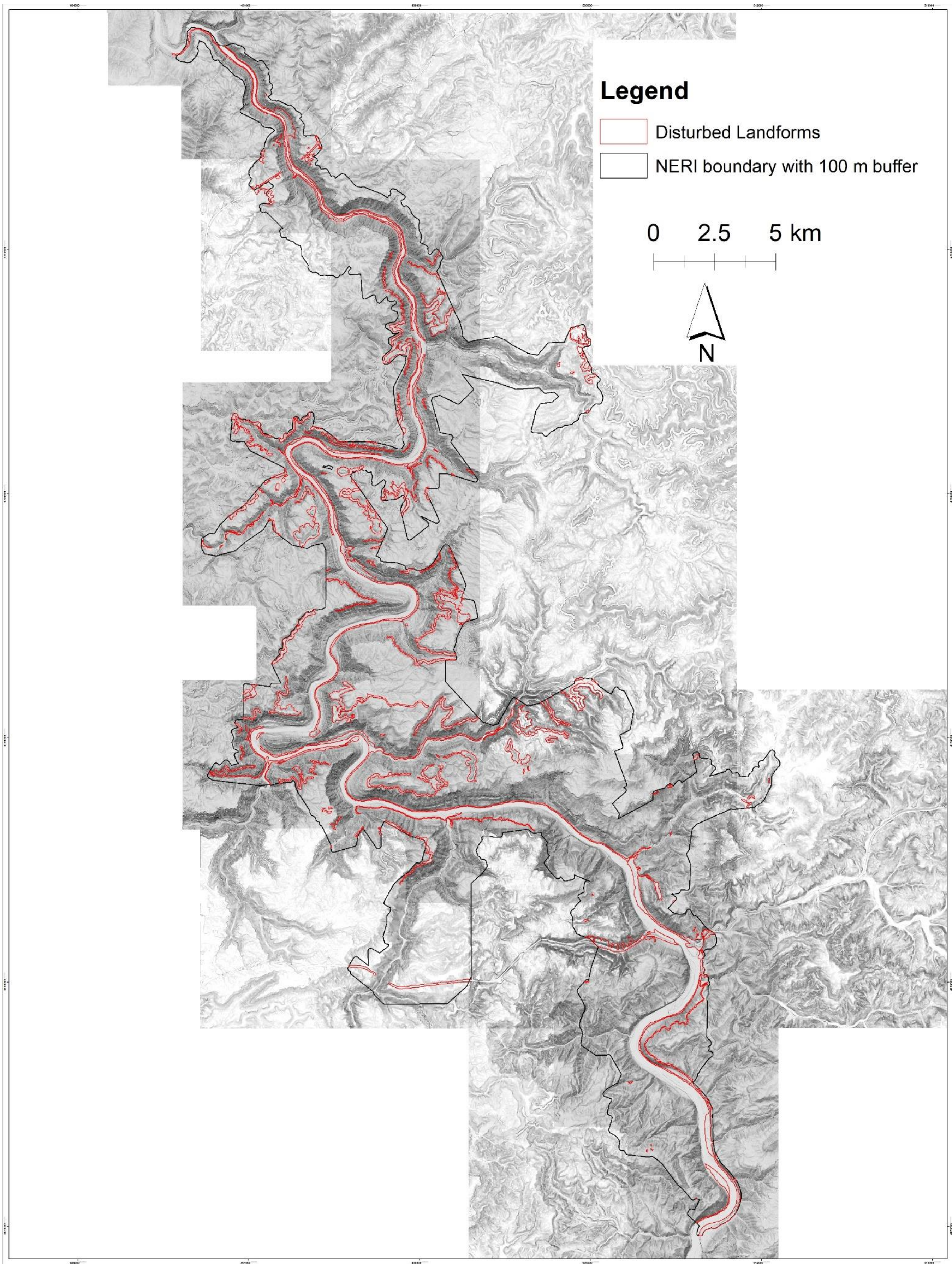

Figure 12. Disturbed landforms in NERI.

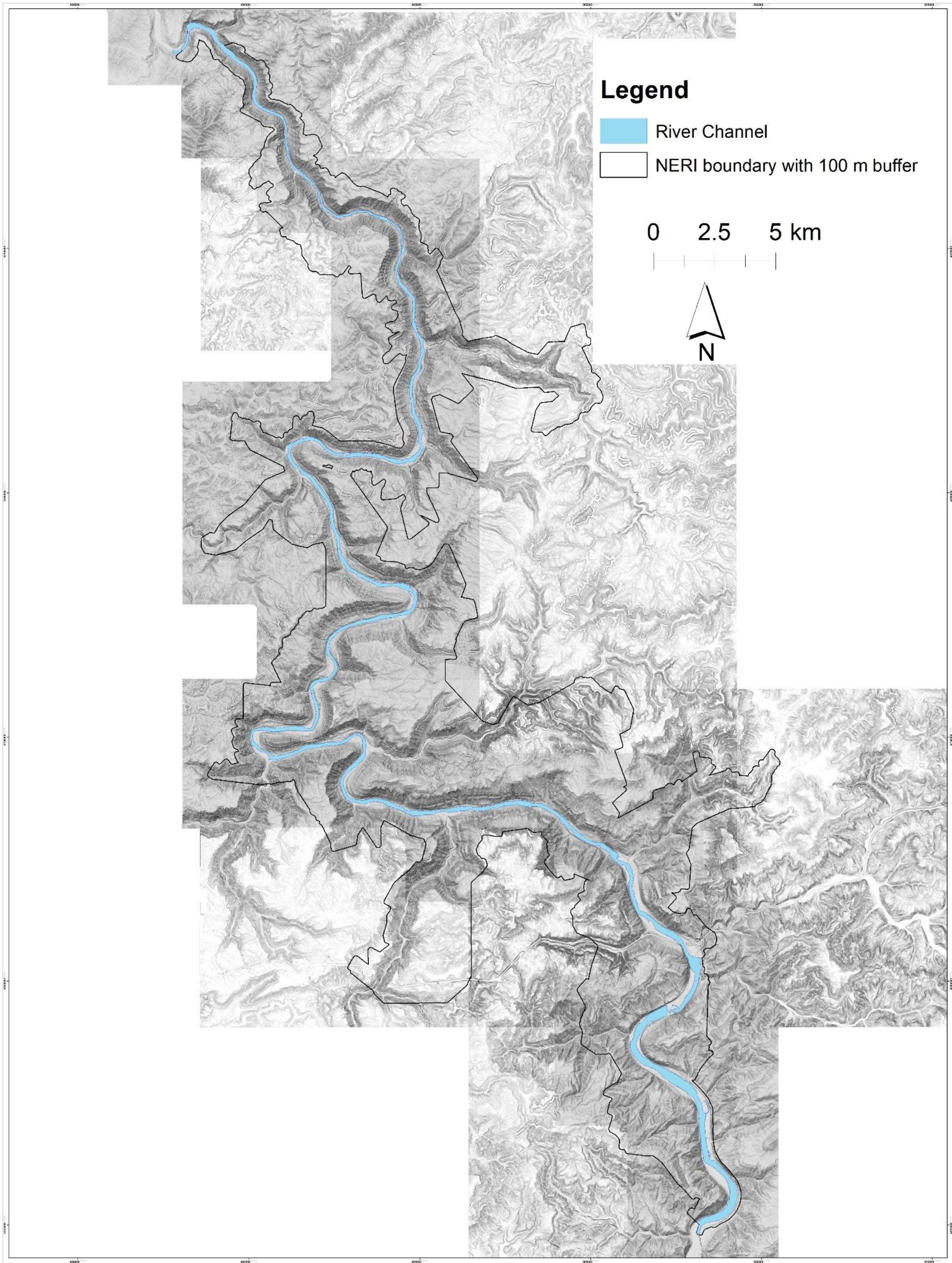

Figure 13. New River channel mapped in NERI.

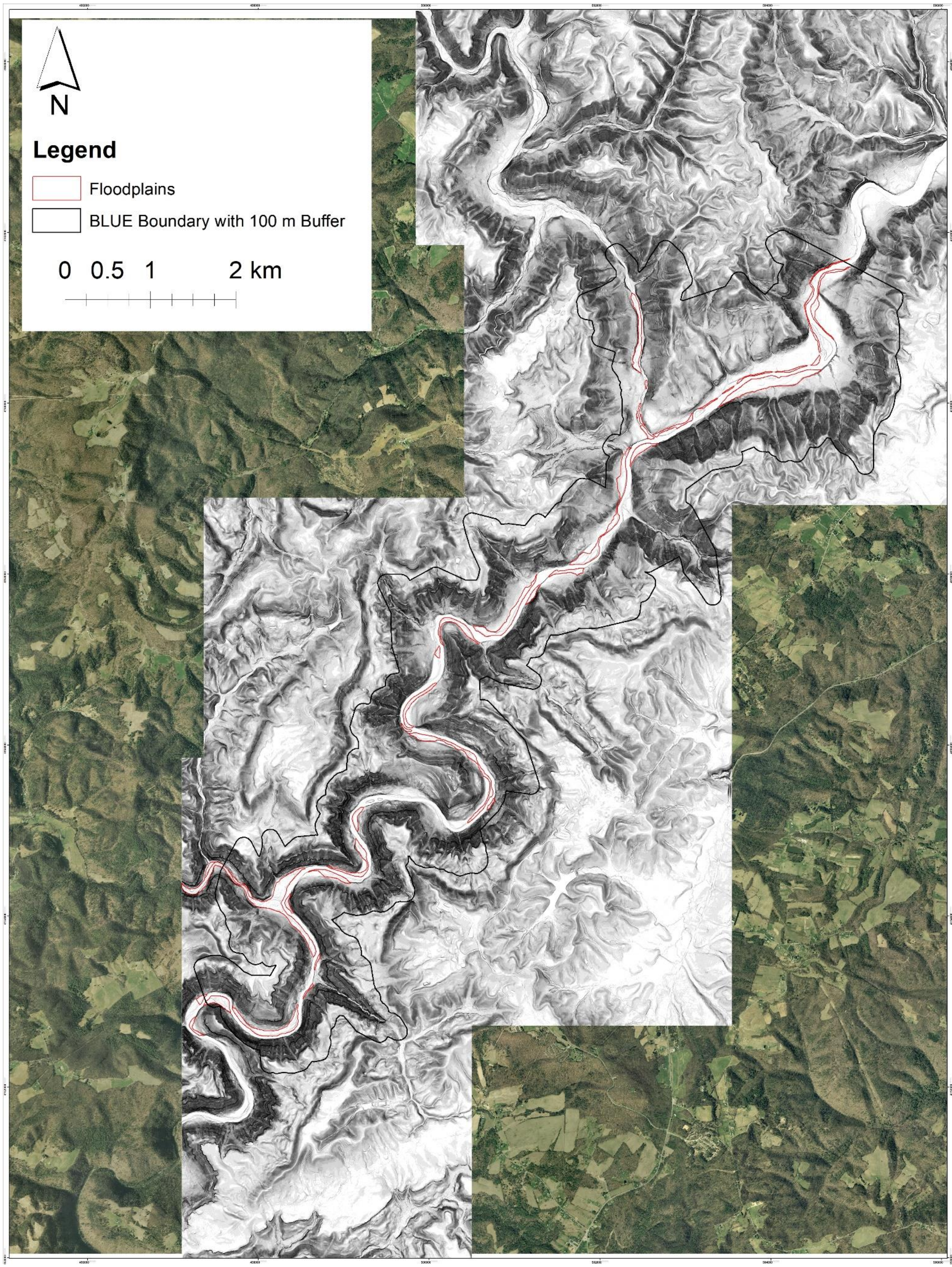

Figure 14. Floodplains in BLUE.

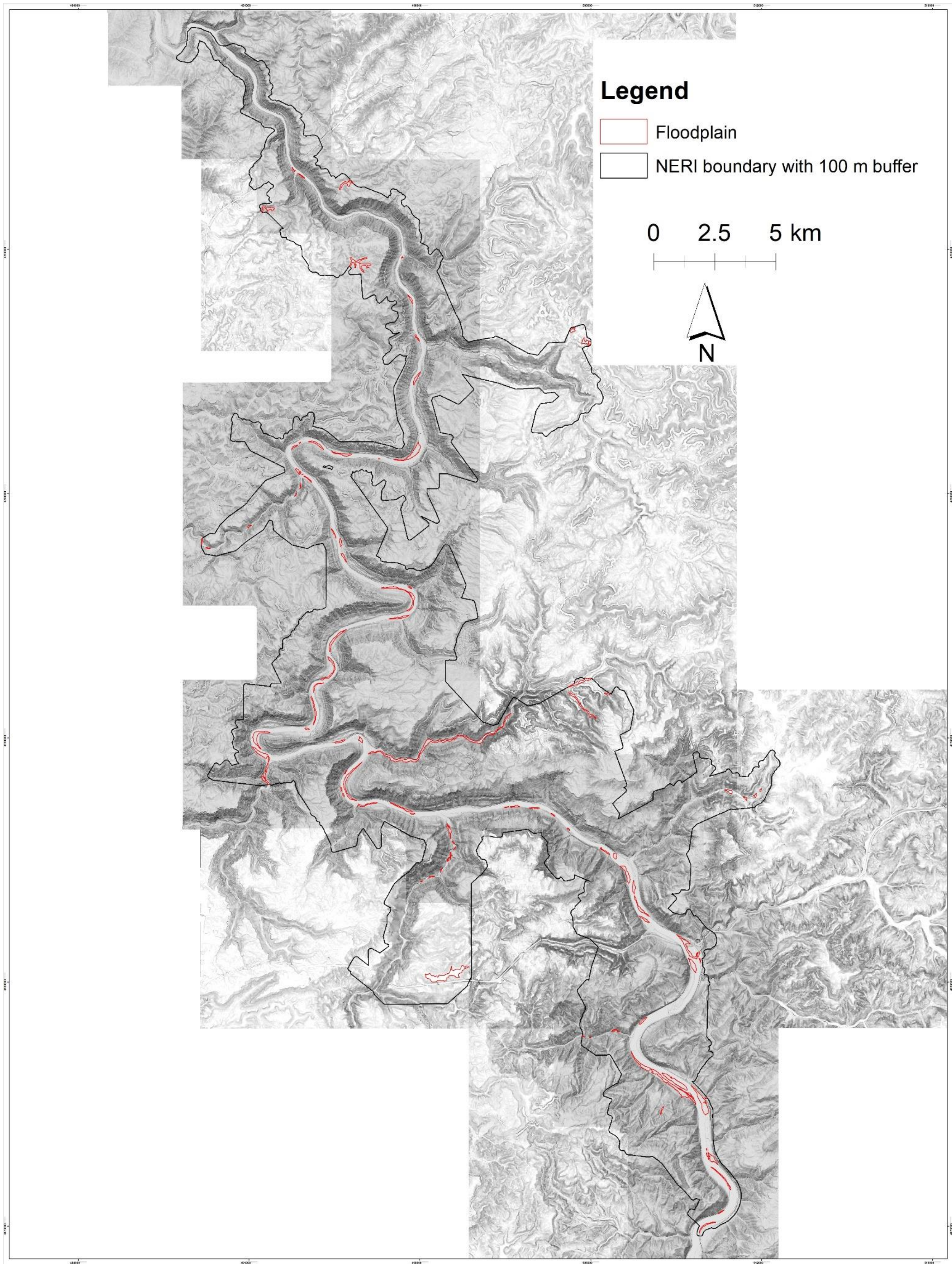

Figure 15. Floodplains in NERI.

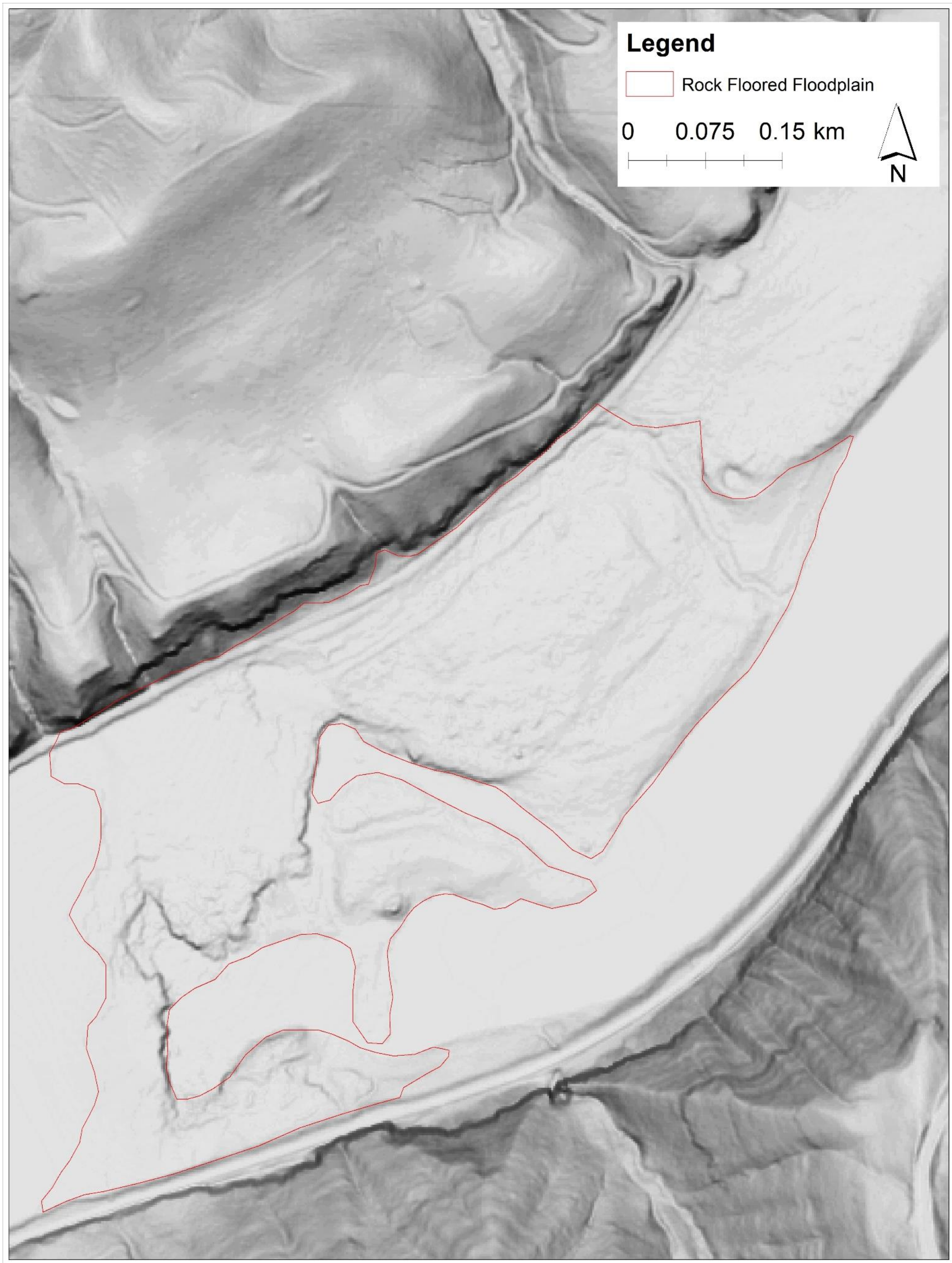

Figure 16. Rock-floored floodplain in upper NERI.

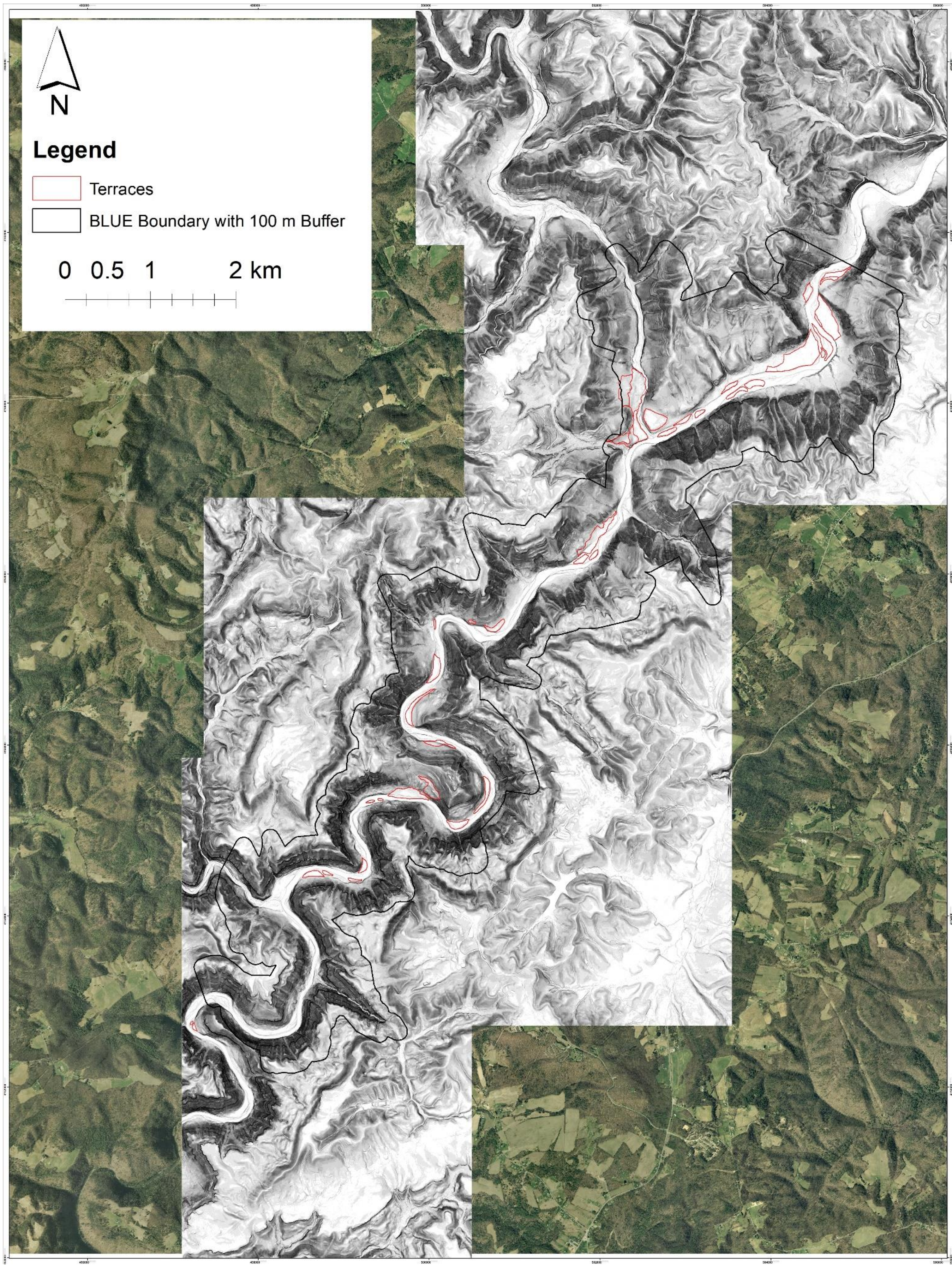

Figure 17. Terraces in BLUE.

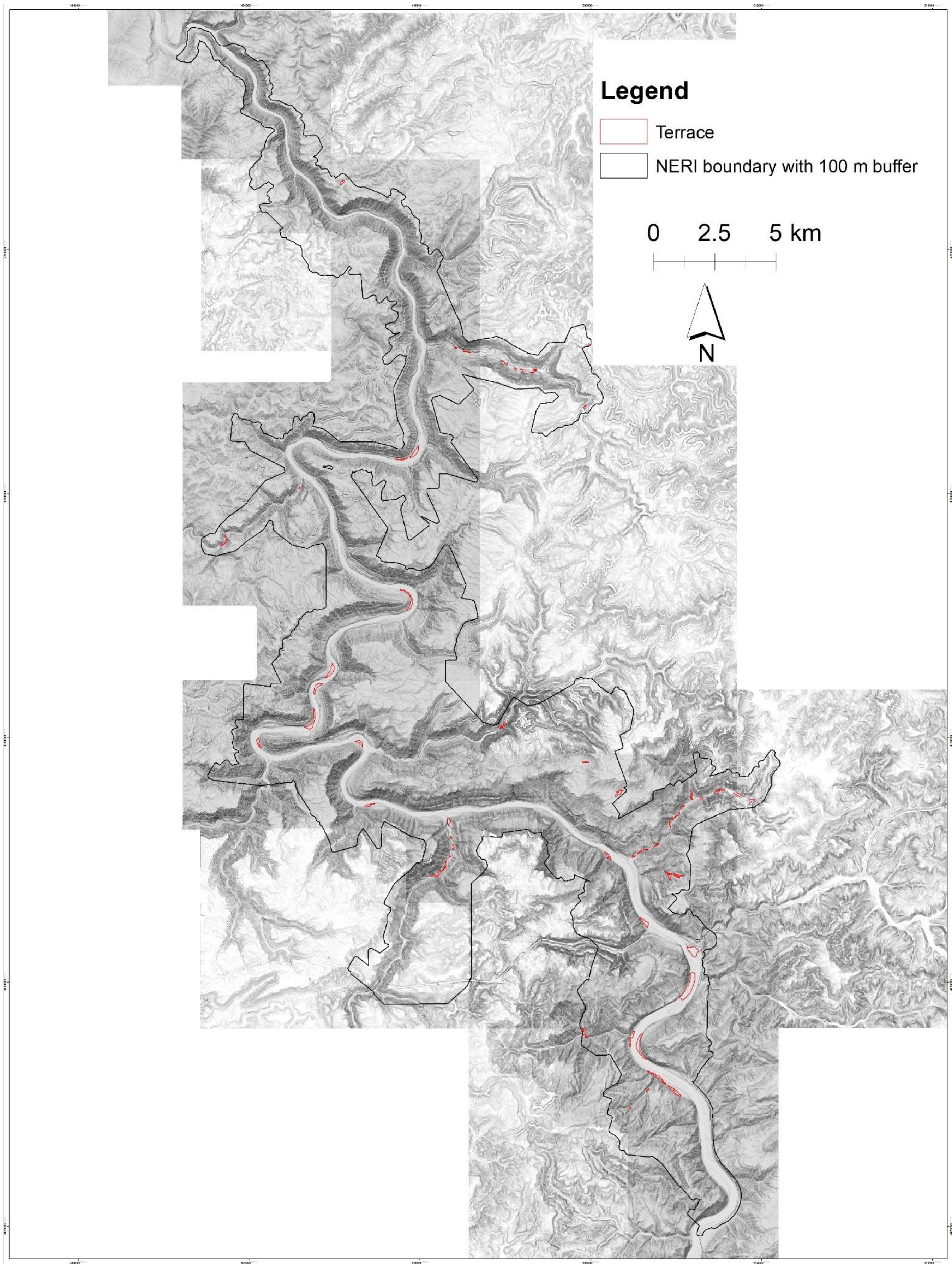

Figure 18. Terraces in NERI.

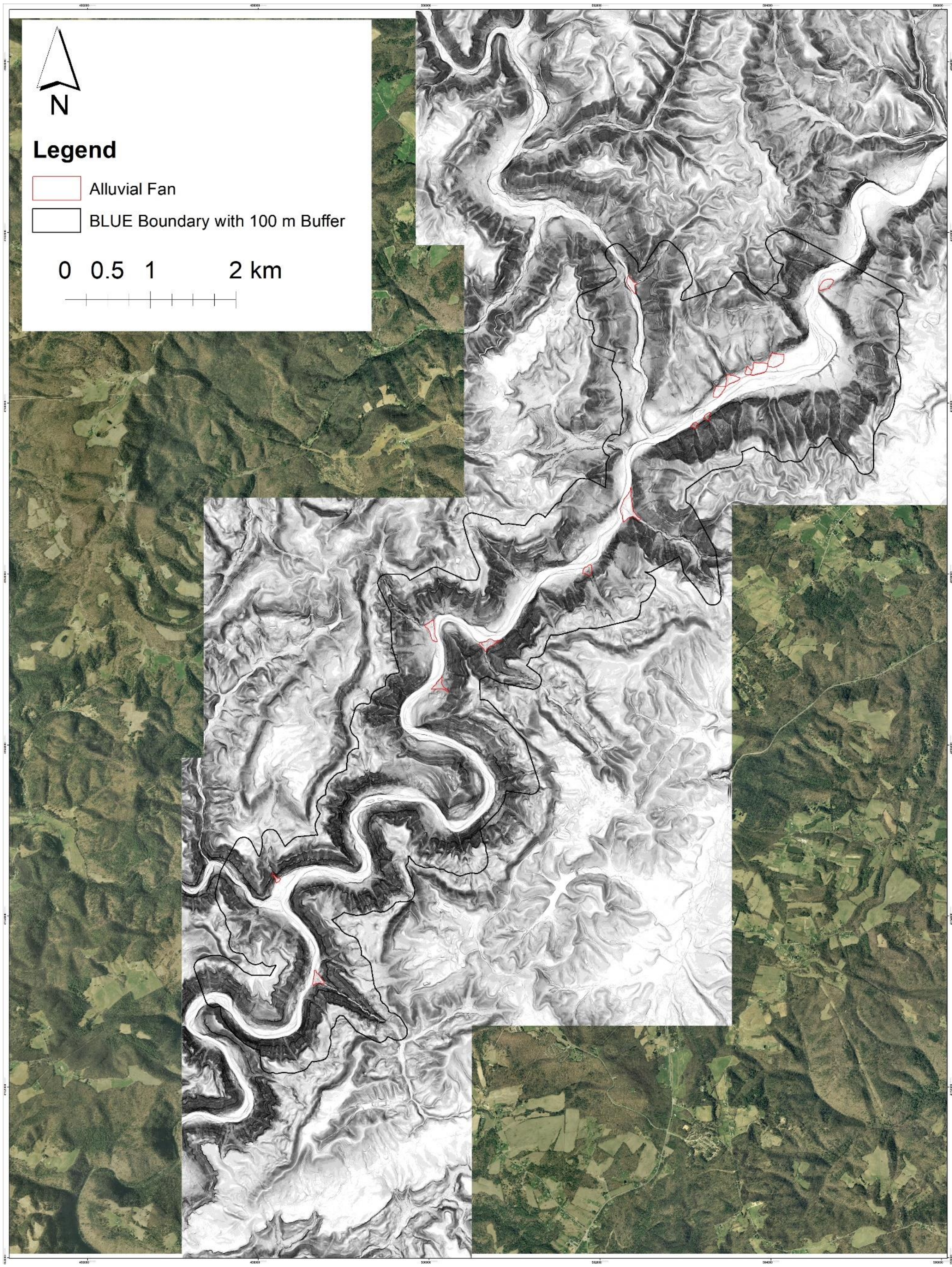

Figure 19. Alluvial fans in BLUE.

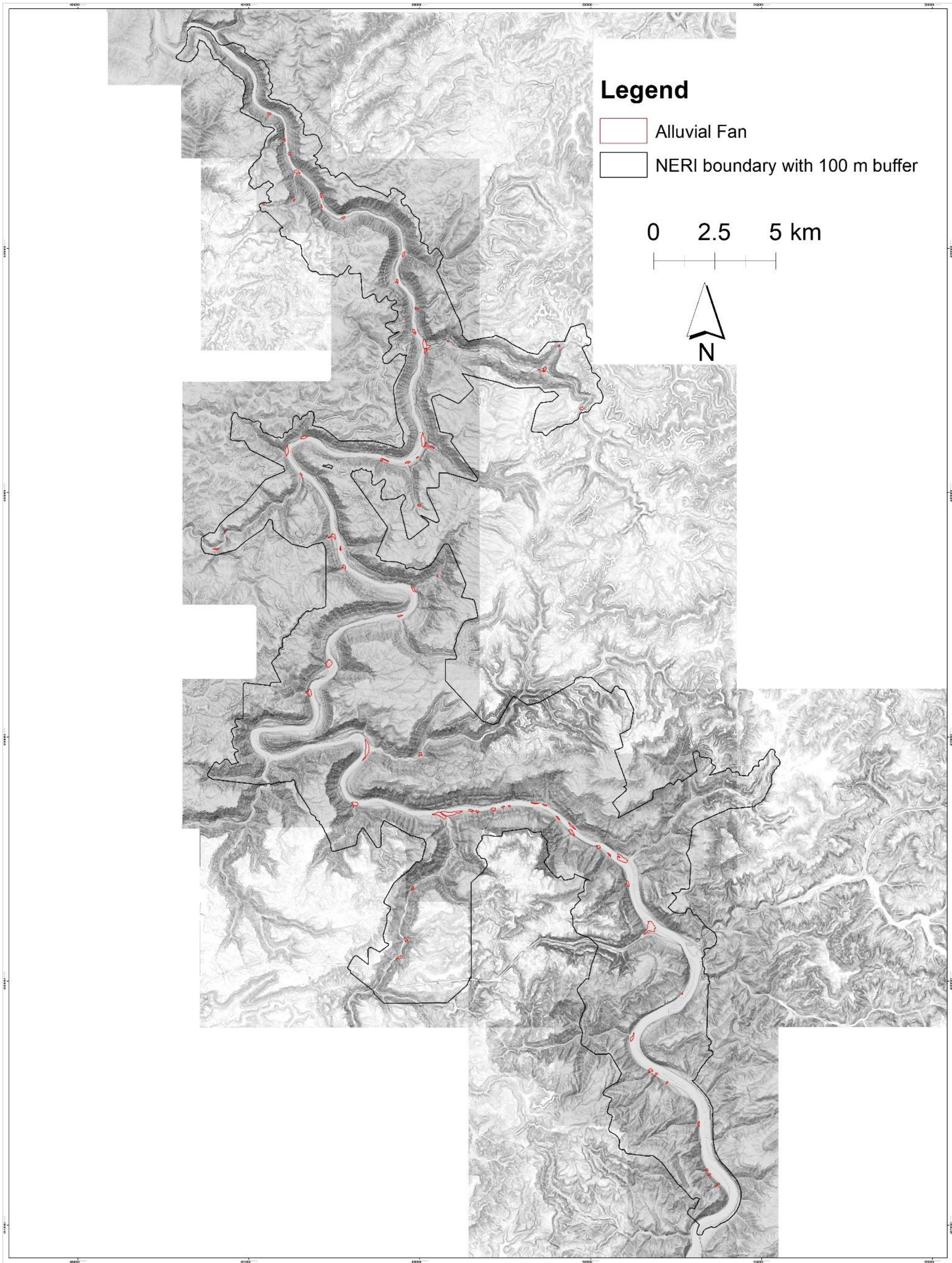

Figure 20. Alluvial fans in NERI.

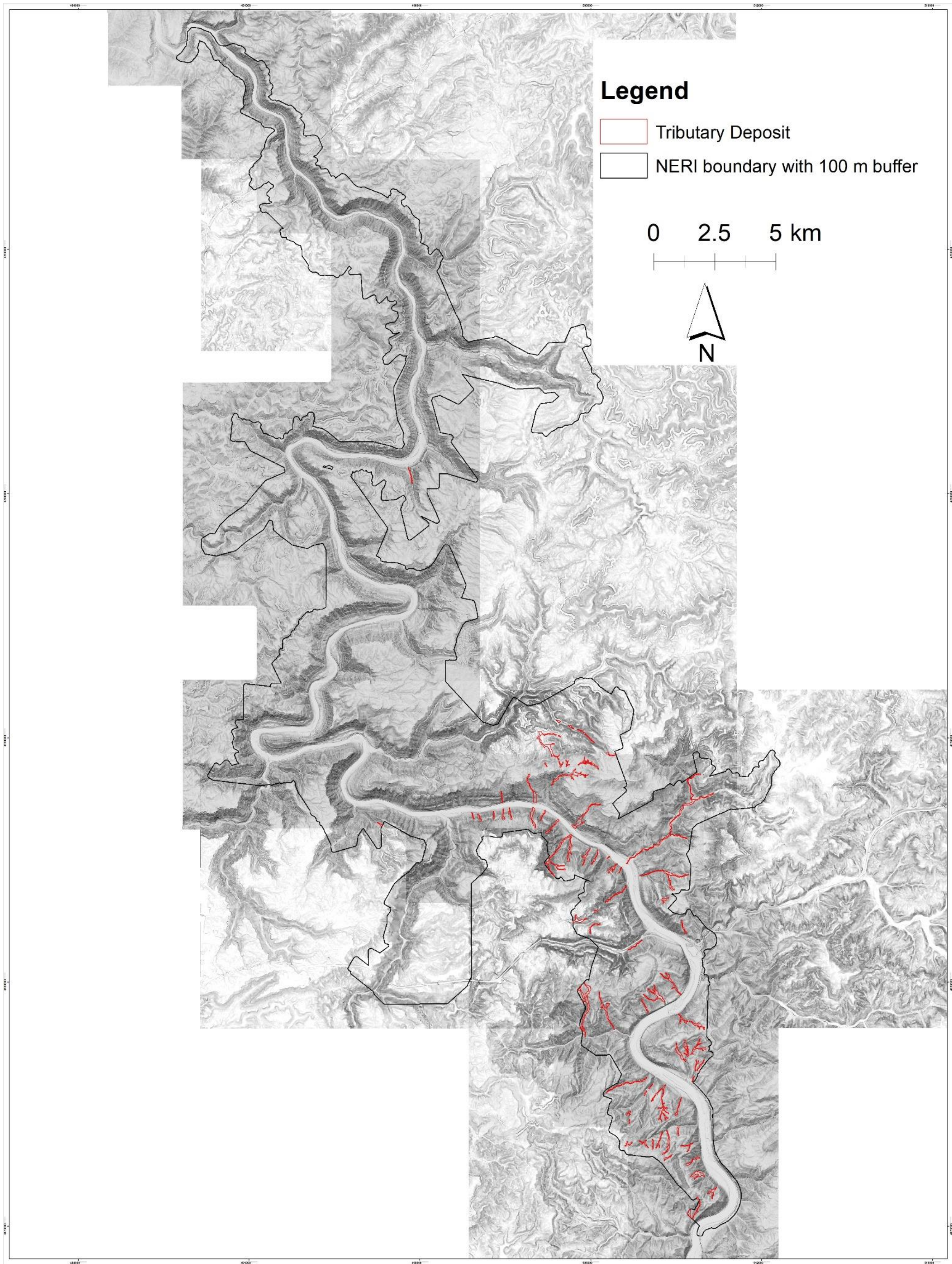

Figure 21. Tributary deposits mapped in NERI.

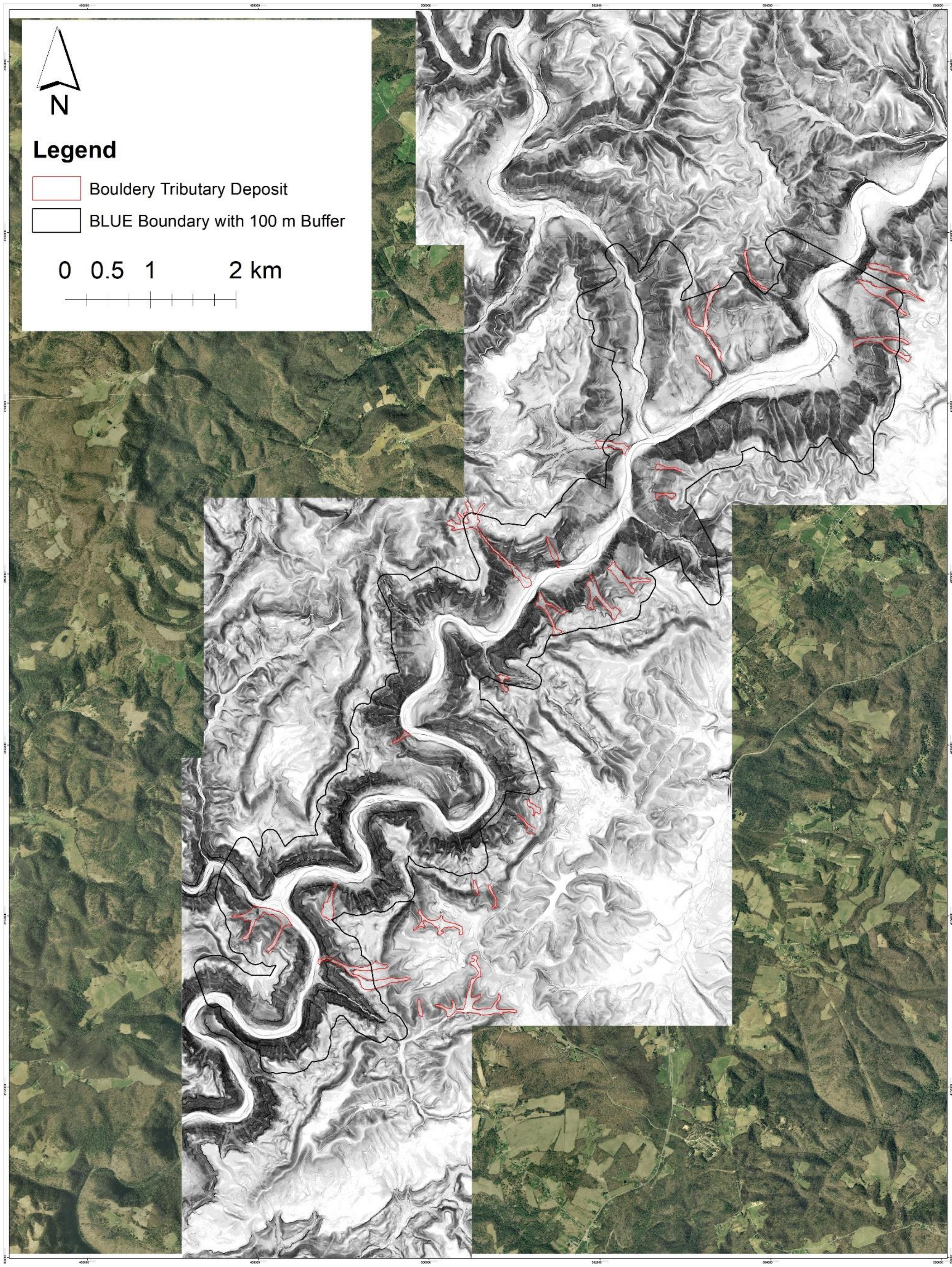

Figure 22. Bouldery tributary deposits in BLUE.

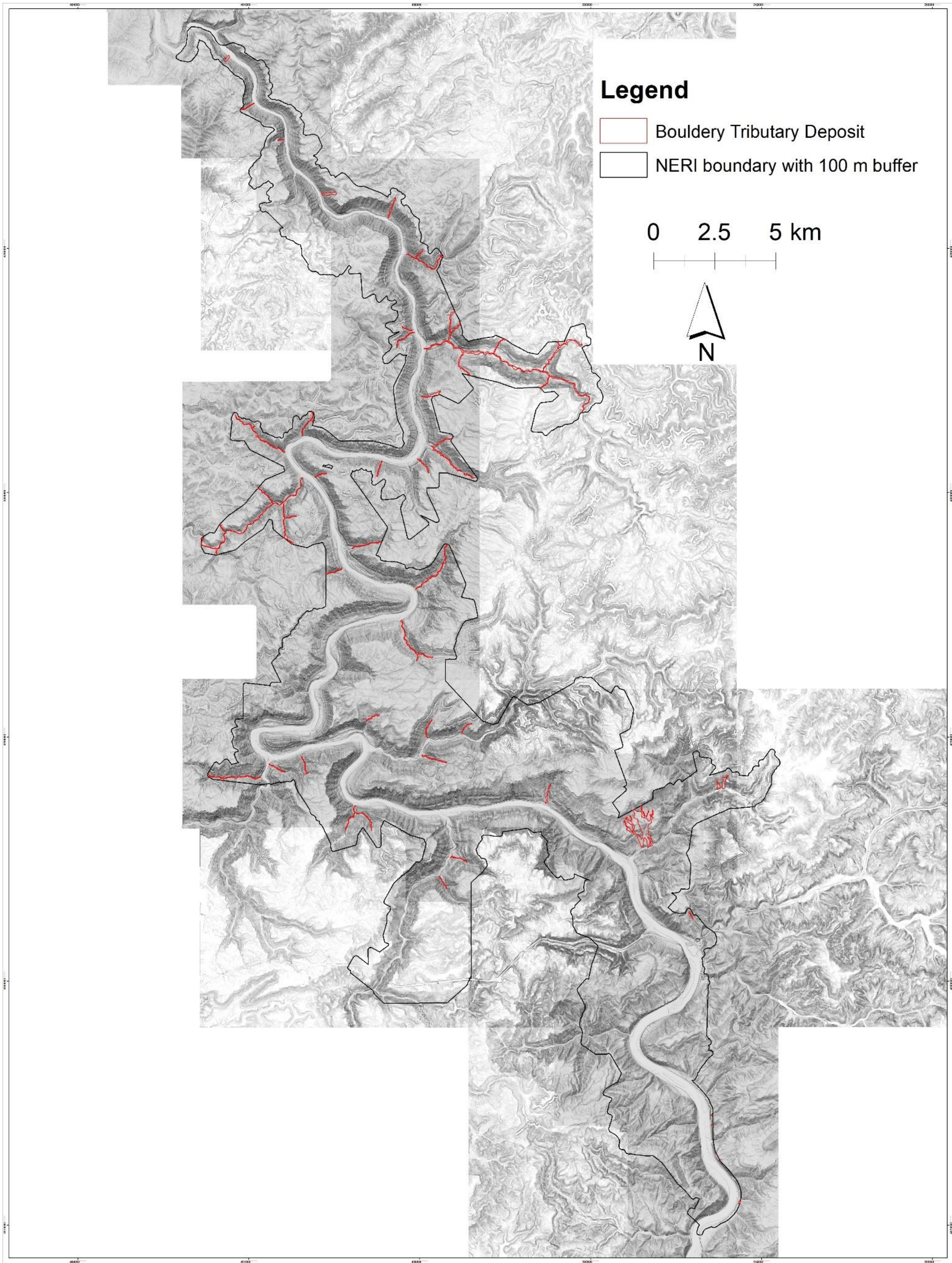

Figure 23. Bouldery tributary deposits in NERI.

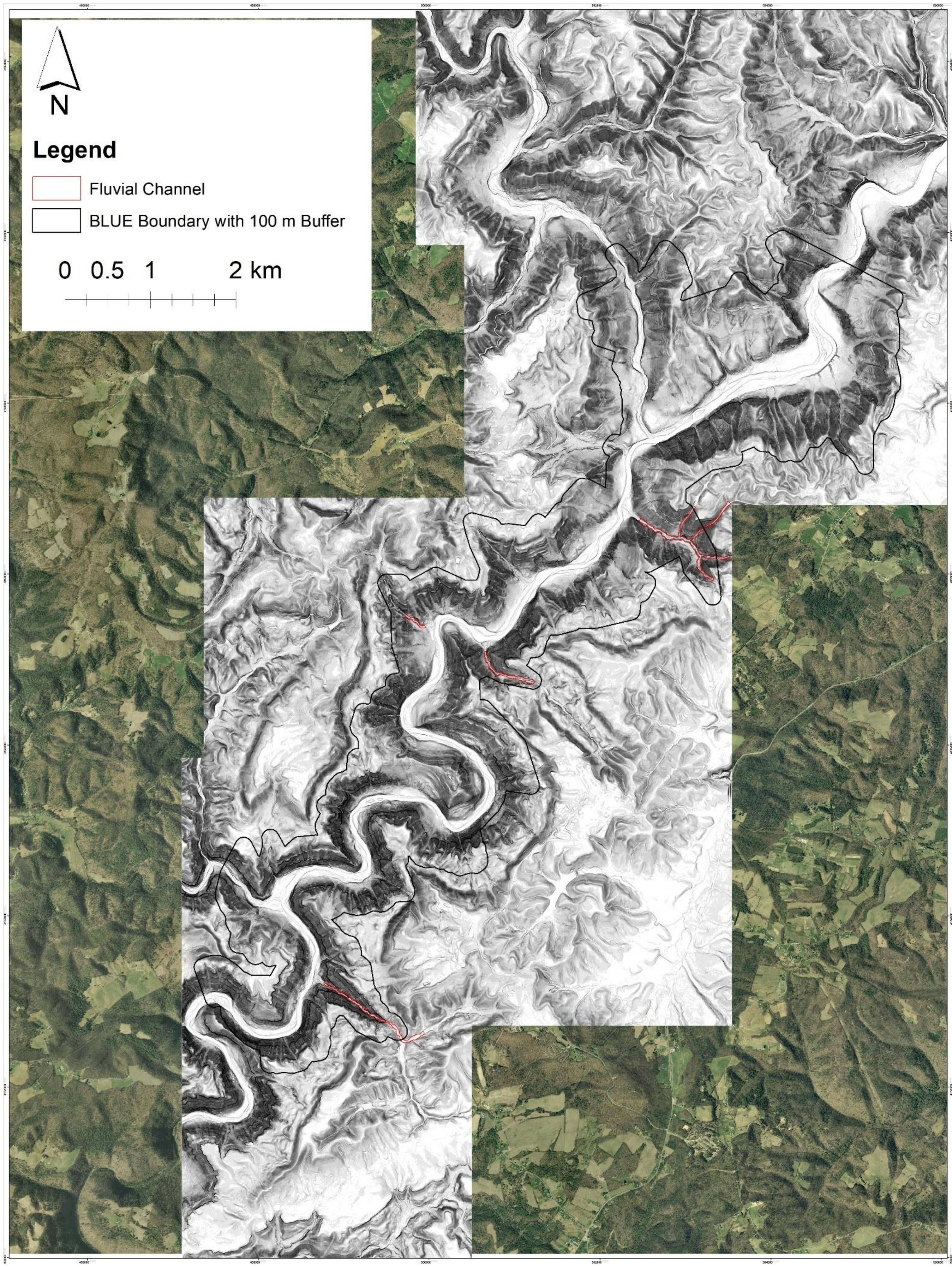

Figure 24. Fluvial channels in BLUE.

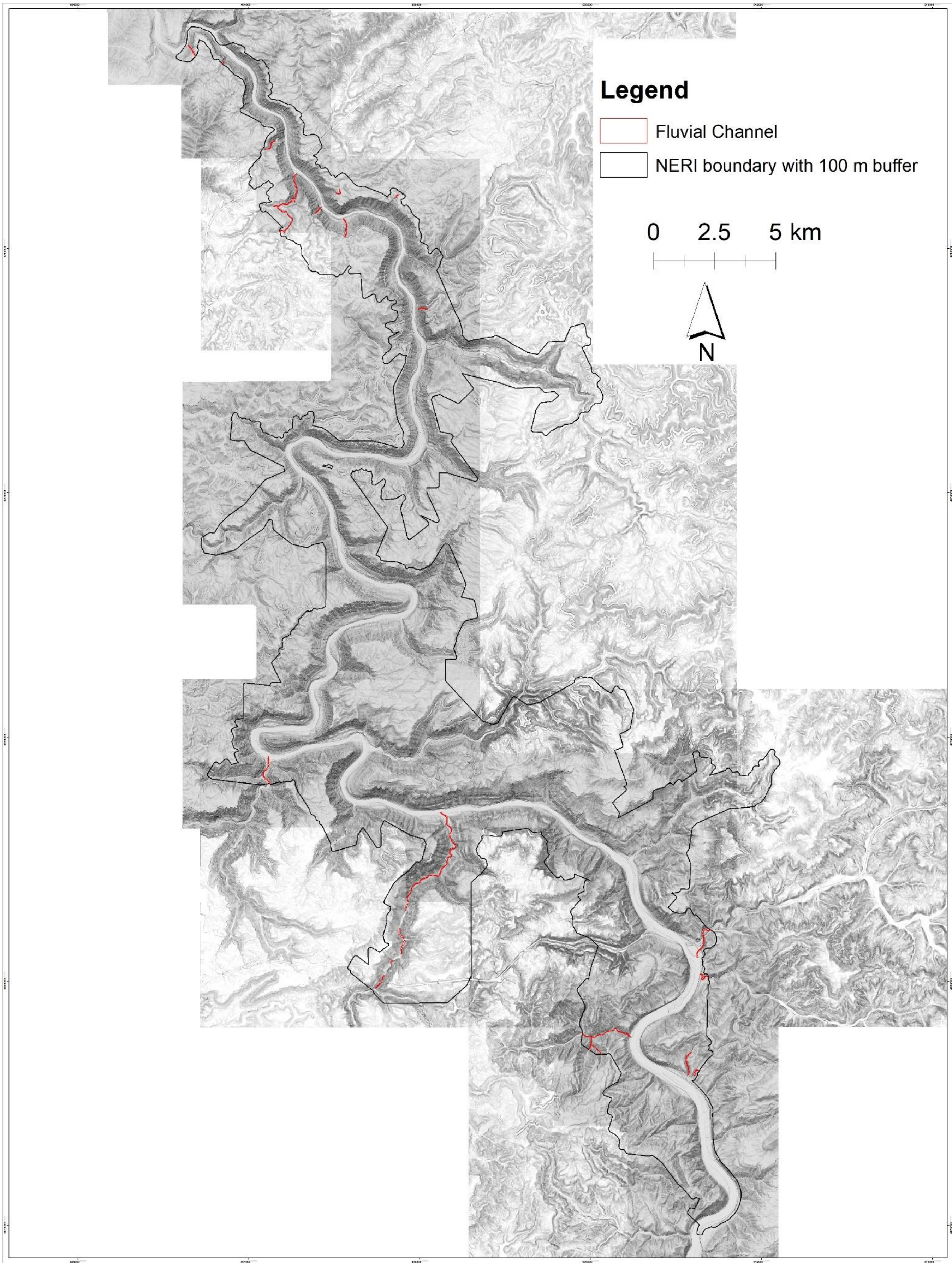

Figure 25. Fluvial channels in NERI.

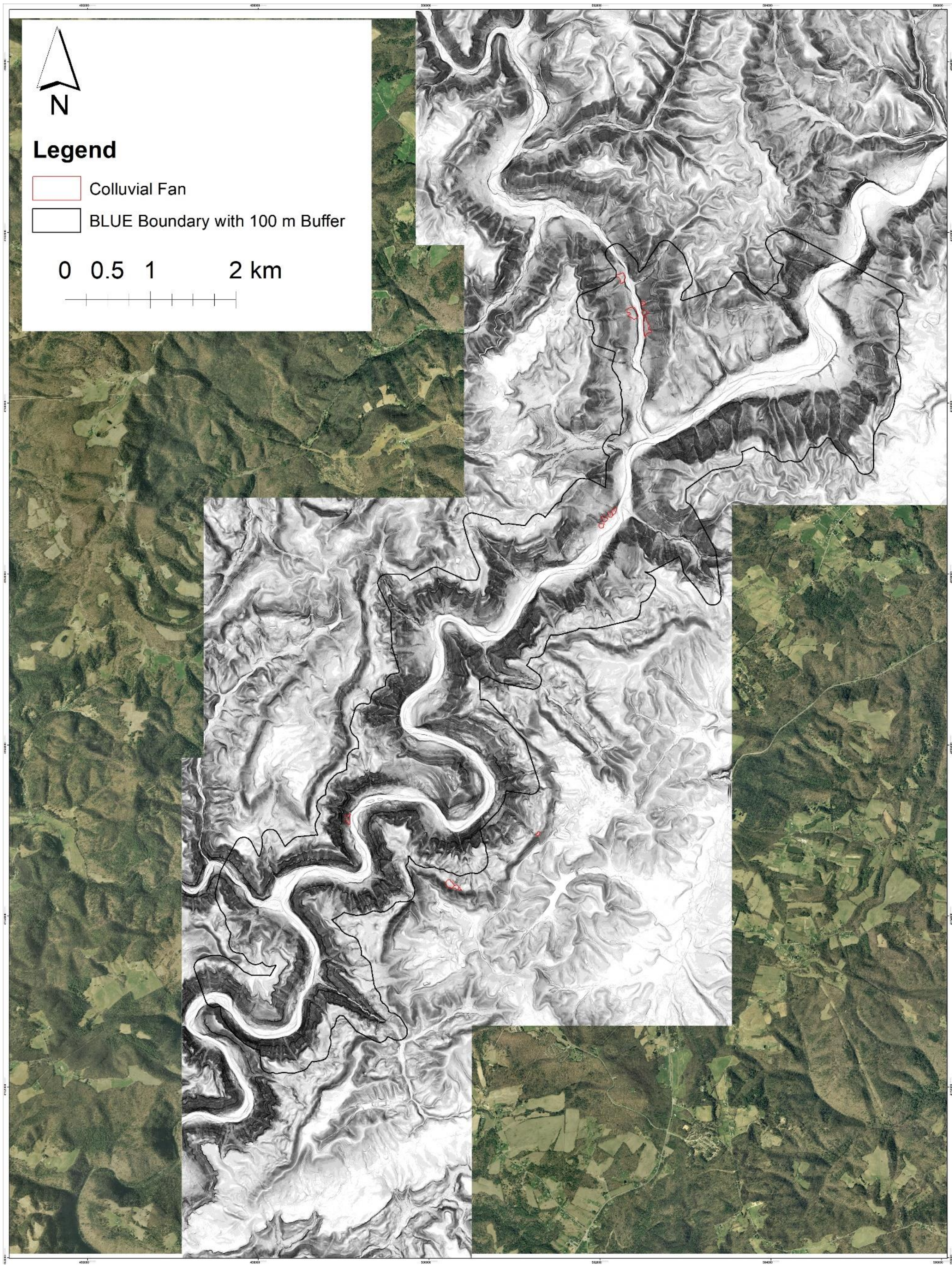

Figure 26. Colluvial fans in BLUE.

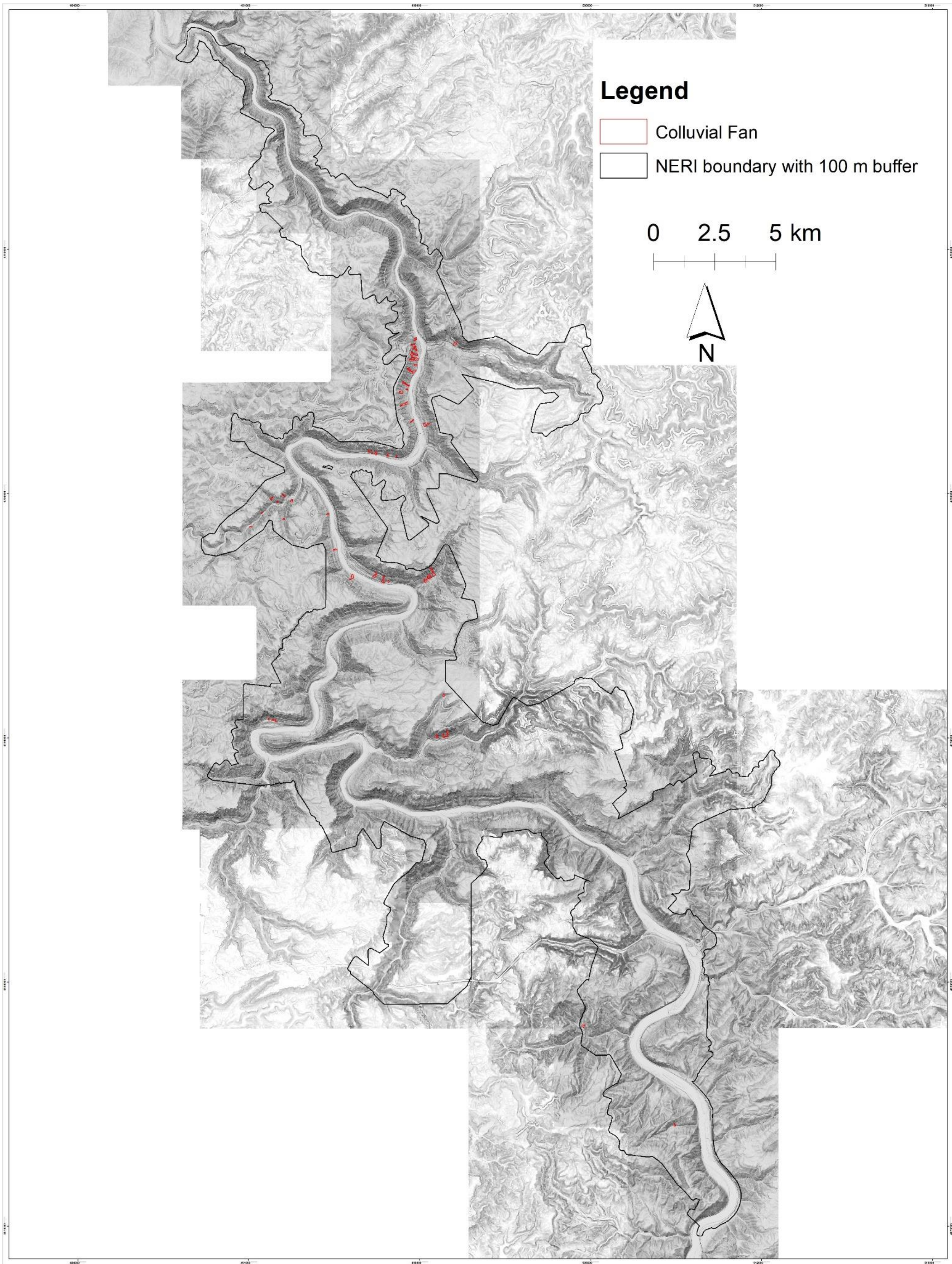

Figure 27. Colluvial fans in NERI.

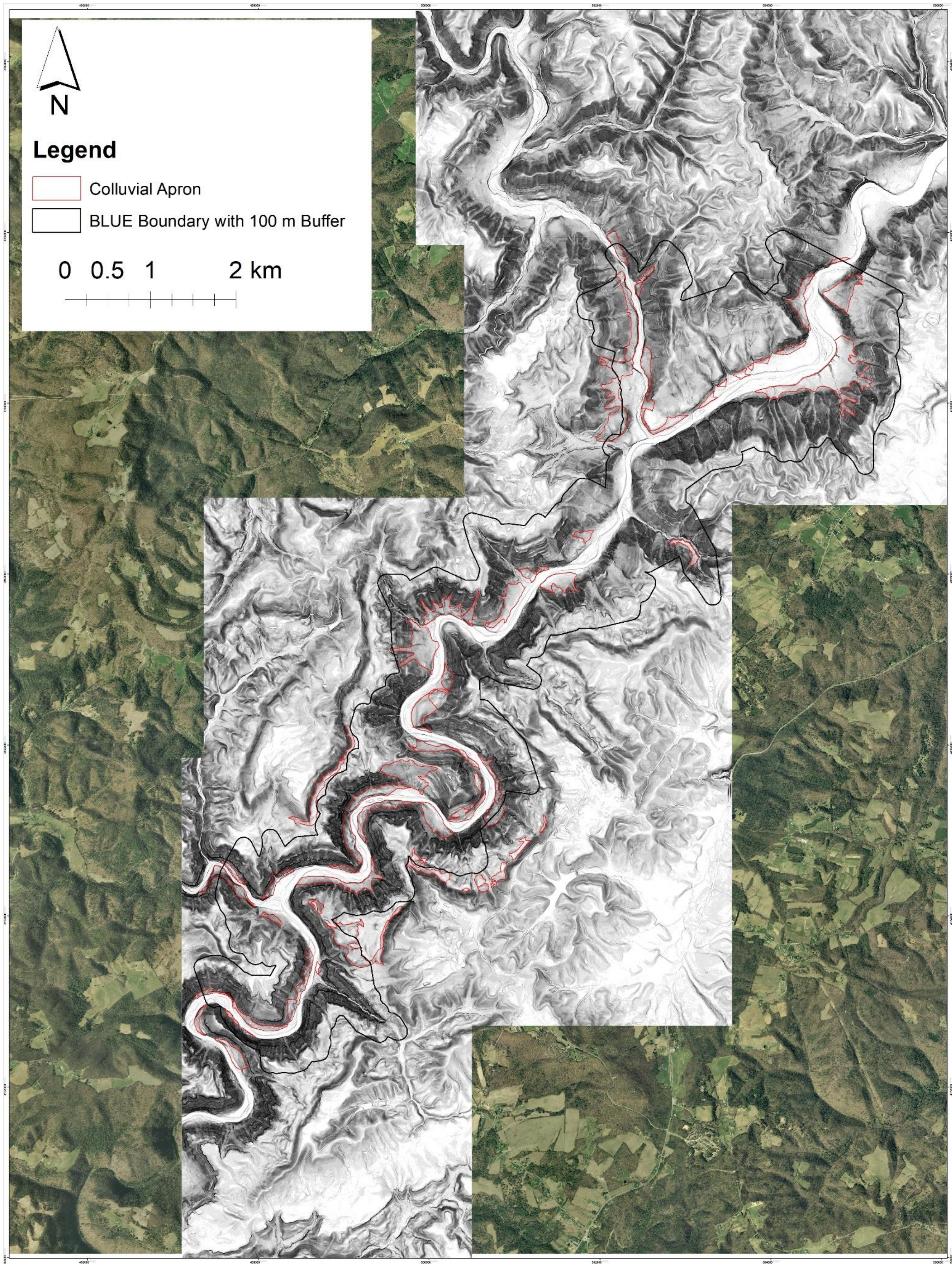

Figure 28. Colluvial aprons in BLUE.

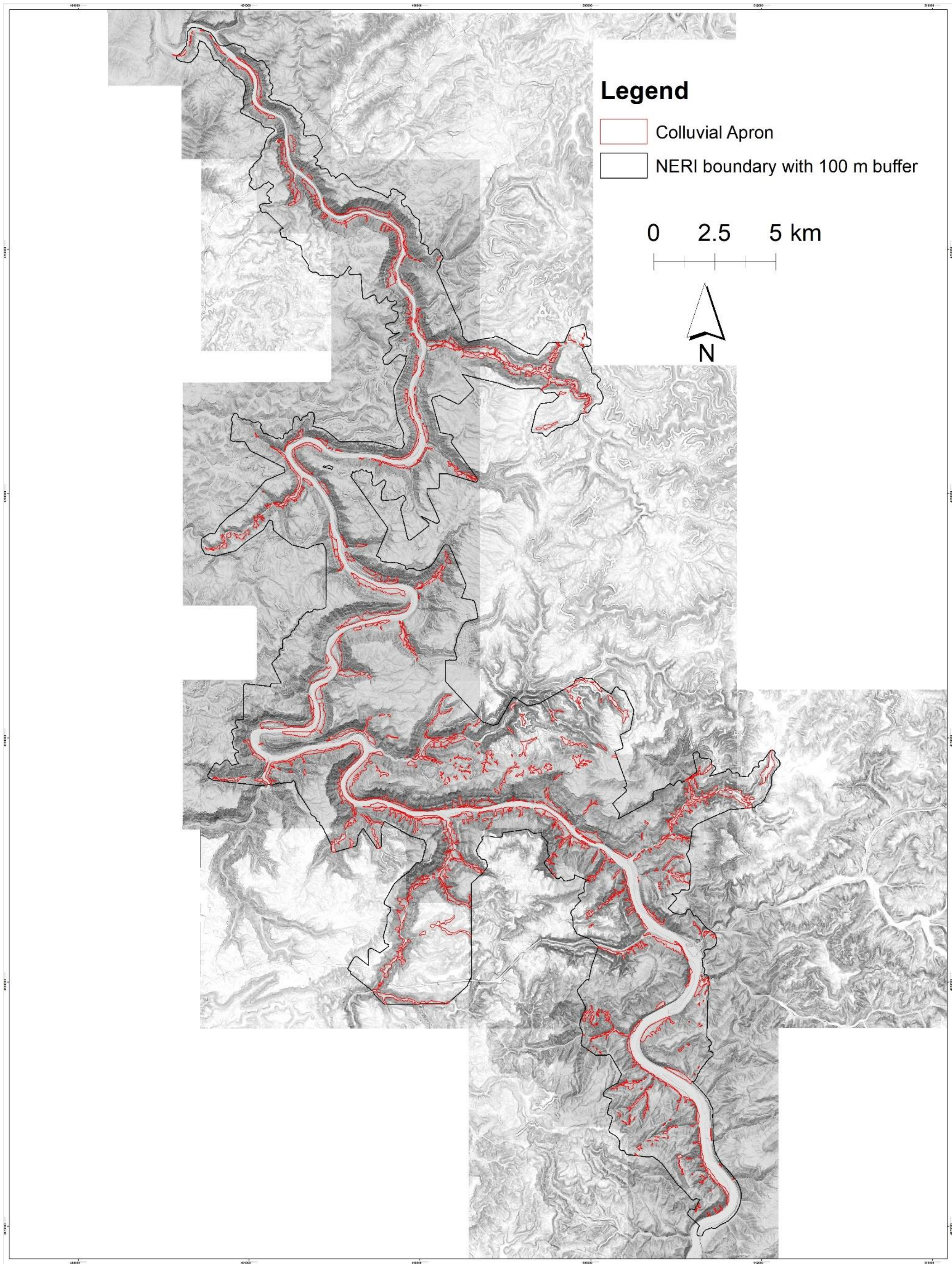

Figure 29. Colluvial aprons in NERI.

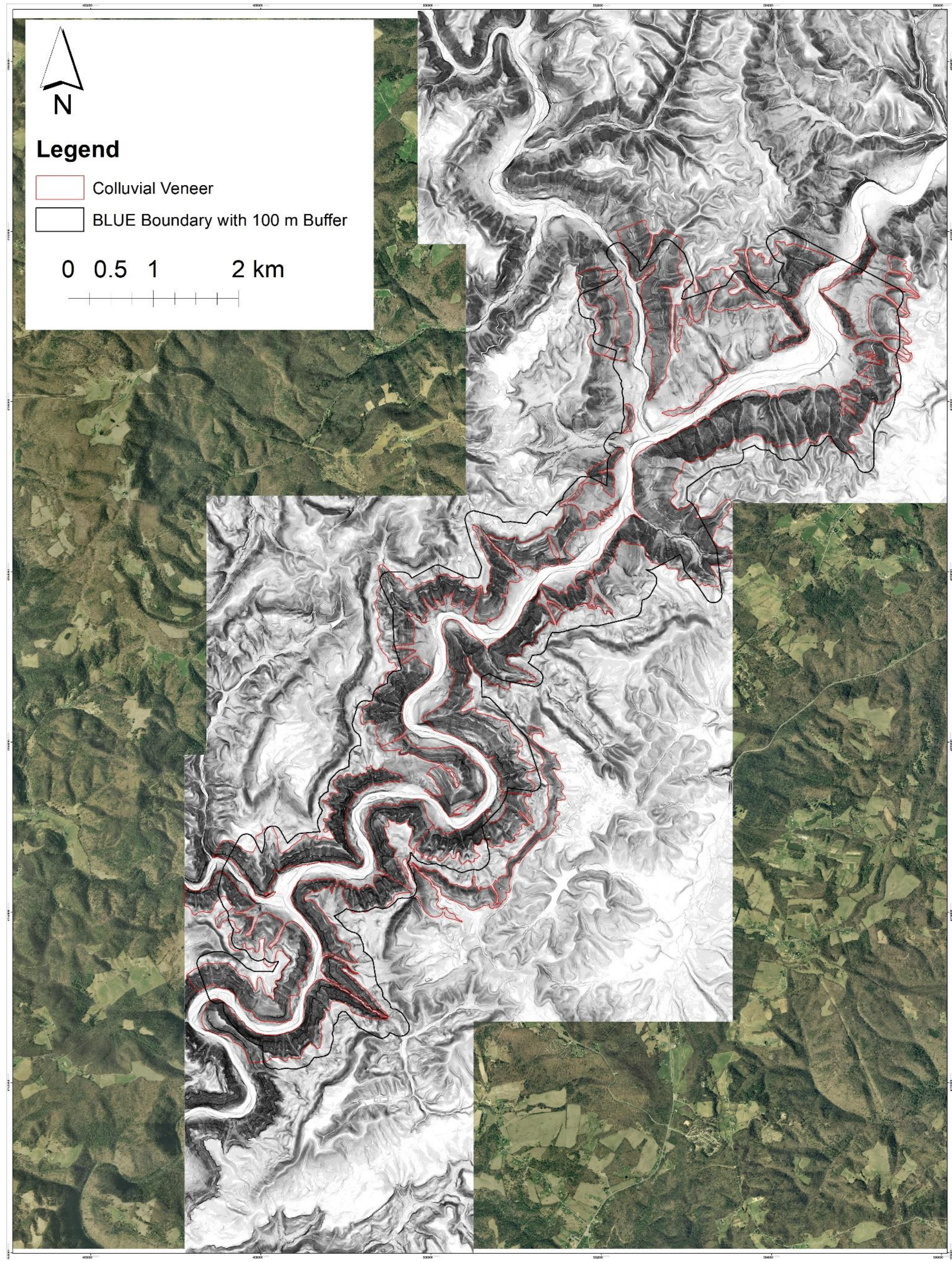

Figure 30. Colluvial veneers in BLUE.

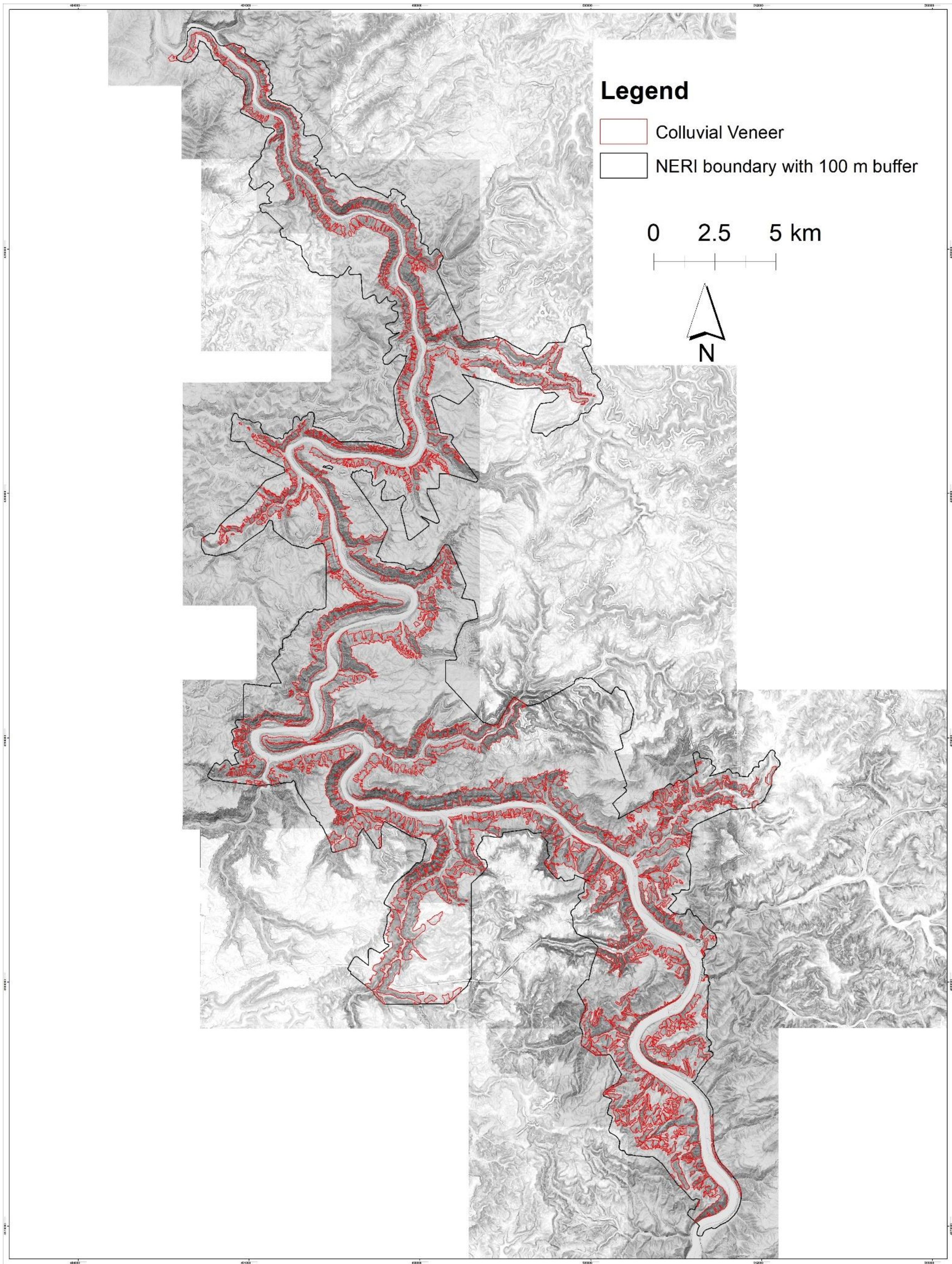

Figure 31. Colluvial veneers in NERI.

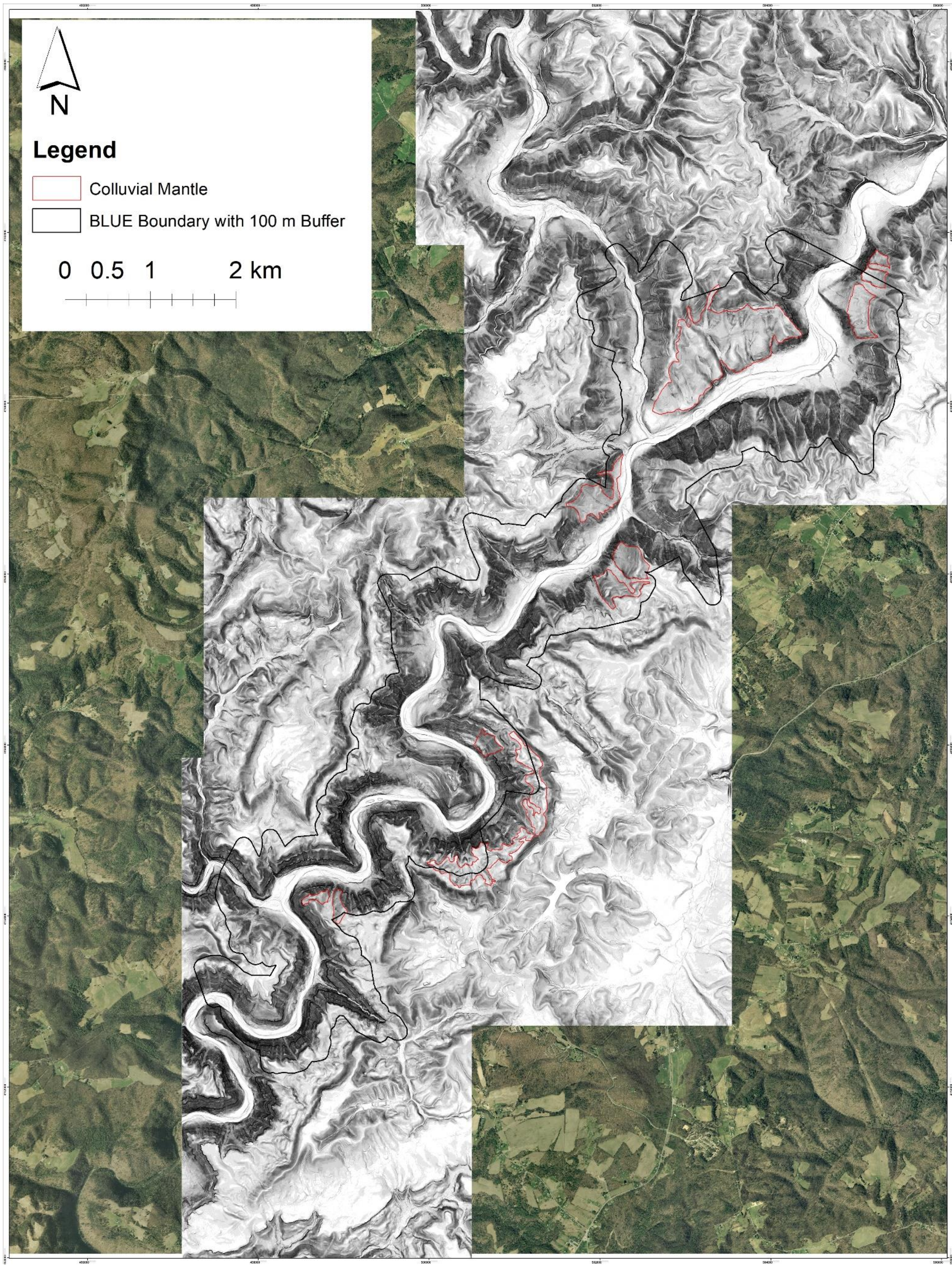

Figure 32. Colluvial mantles in BLUE.

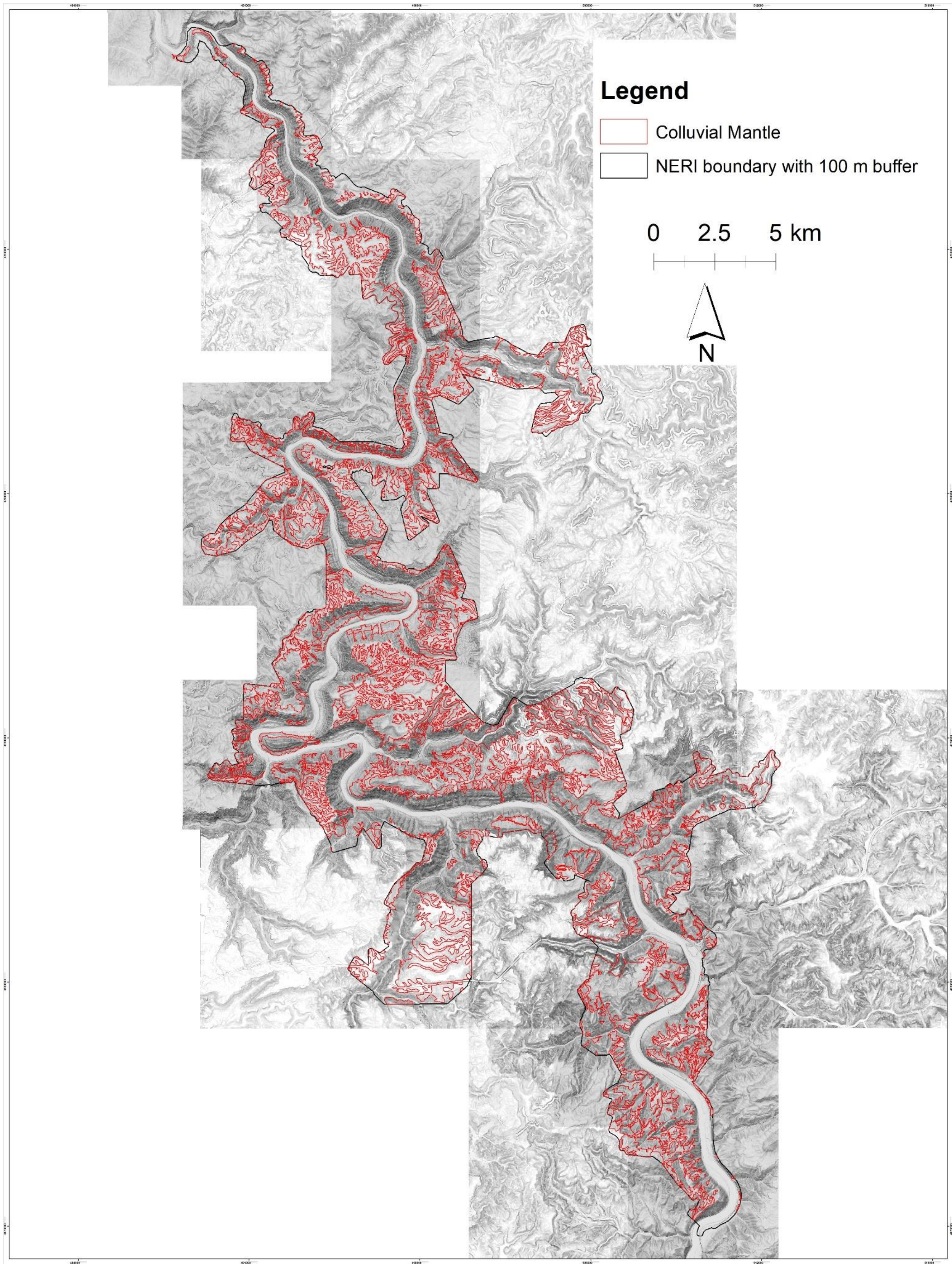

Figure 33. Colluvial mantles in NERI.

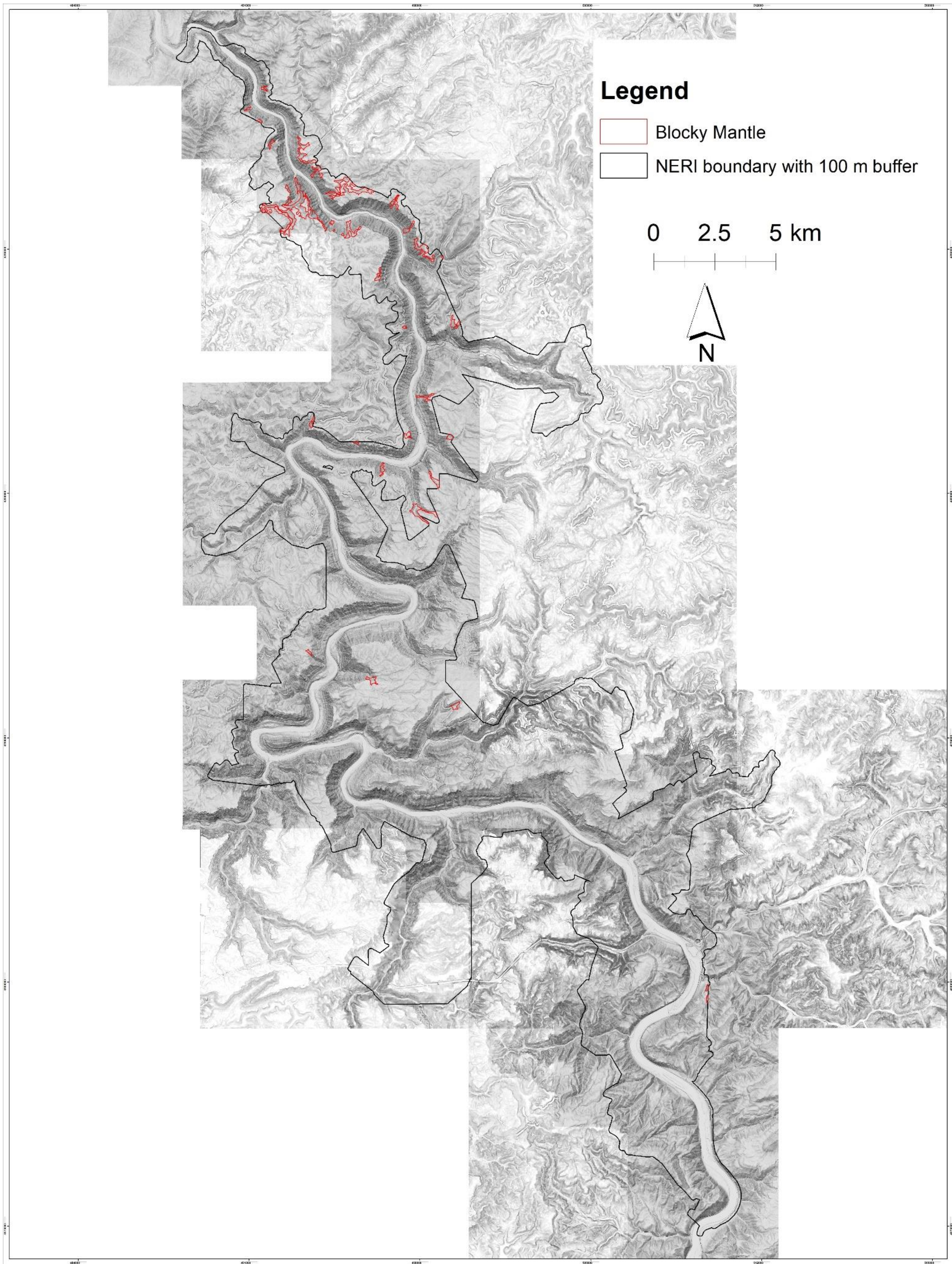

Figure 34. Blocky mantles in NERI.

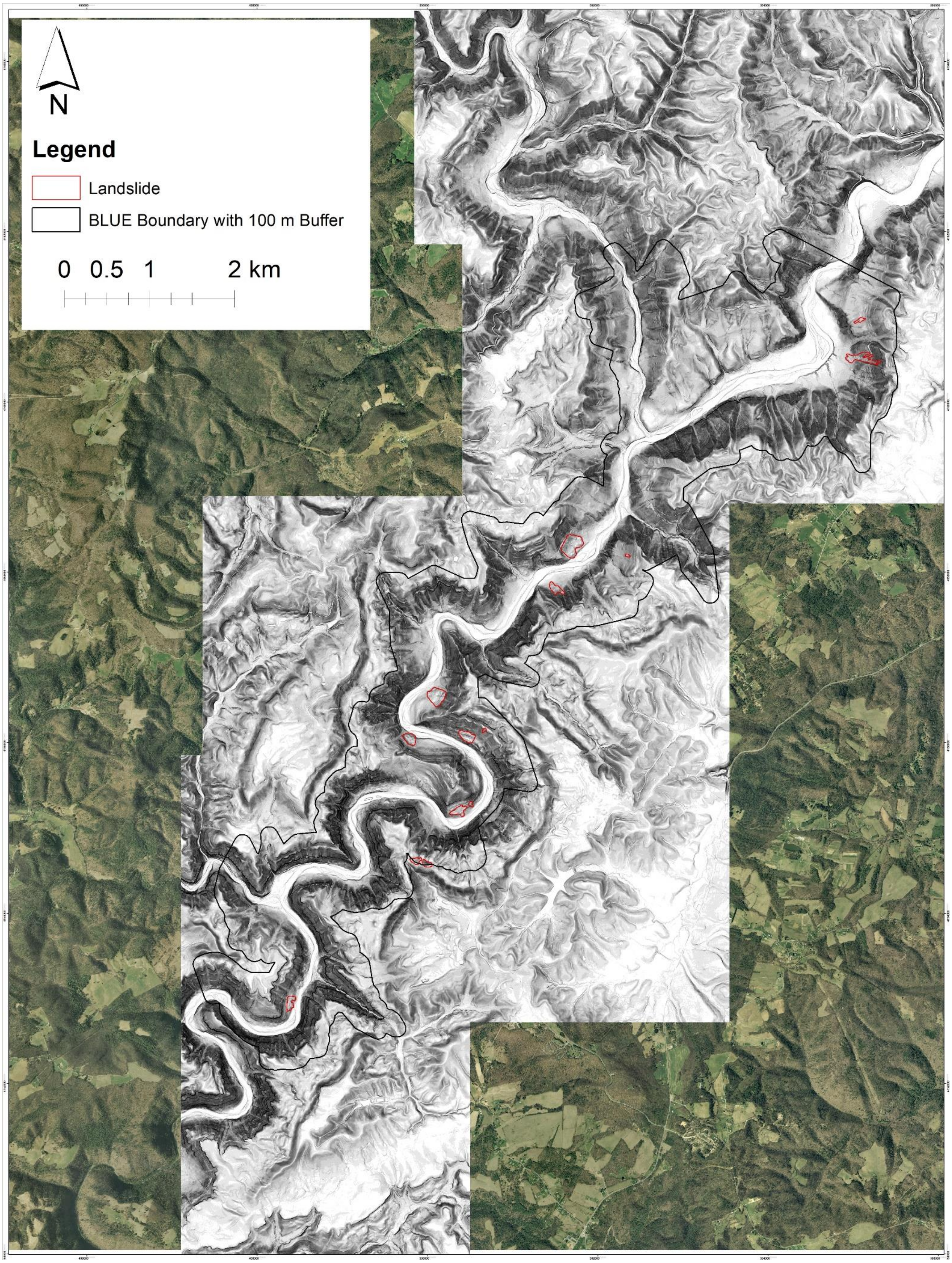

Figure 35. Landslides within BLUE.

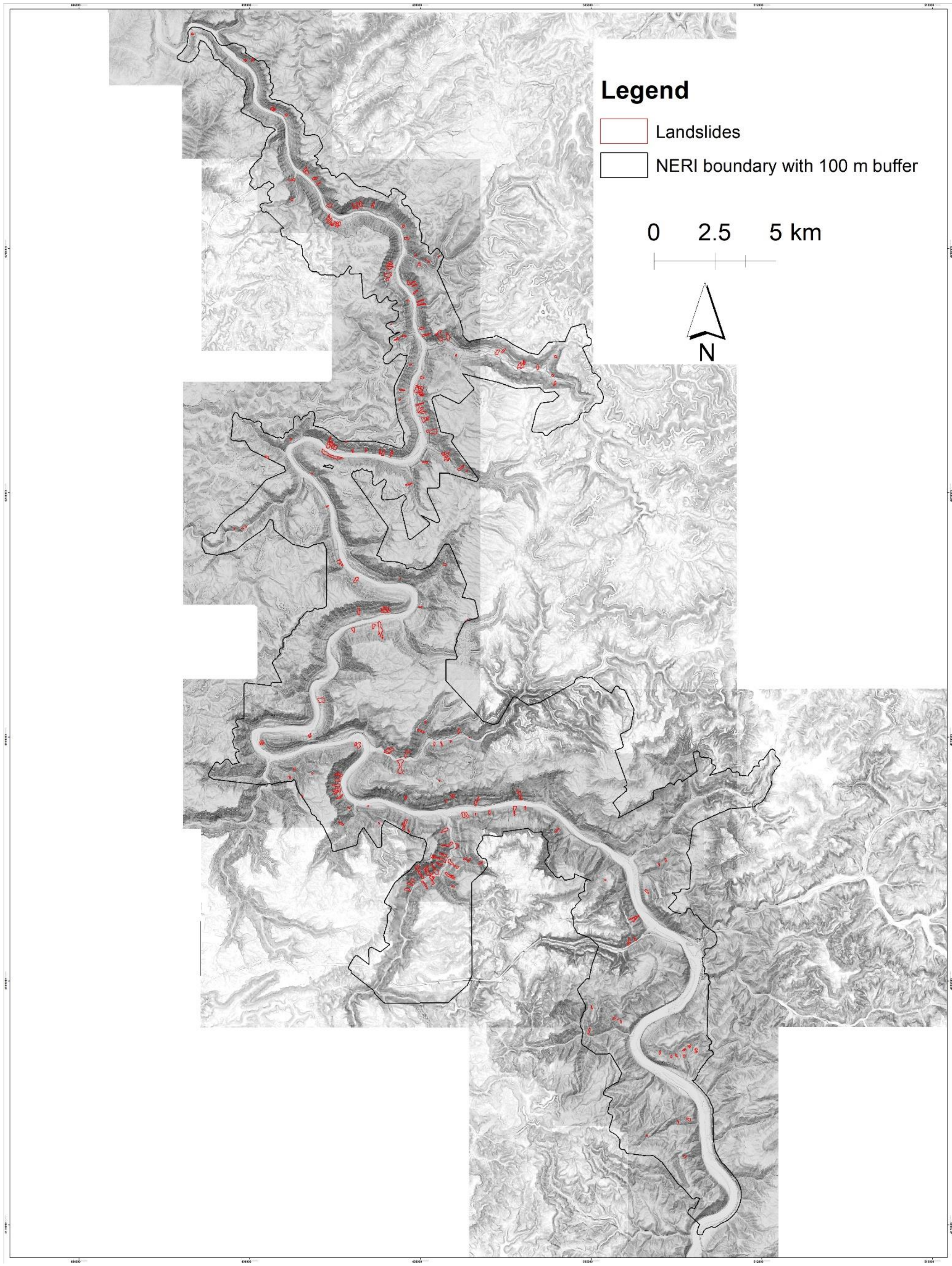

Figure 36. Landslides within NERI.

Figure 37. Photograph of Elverton landslide in middle NERI (Katherine Paybins, USGS photo).

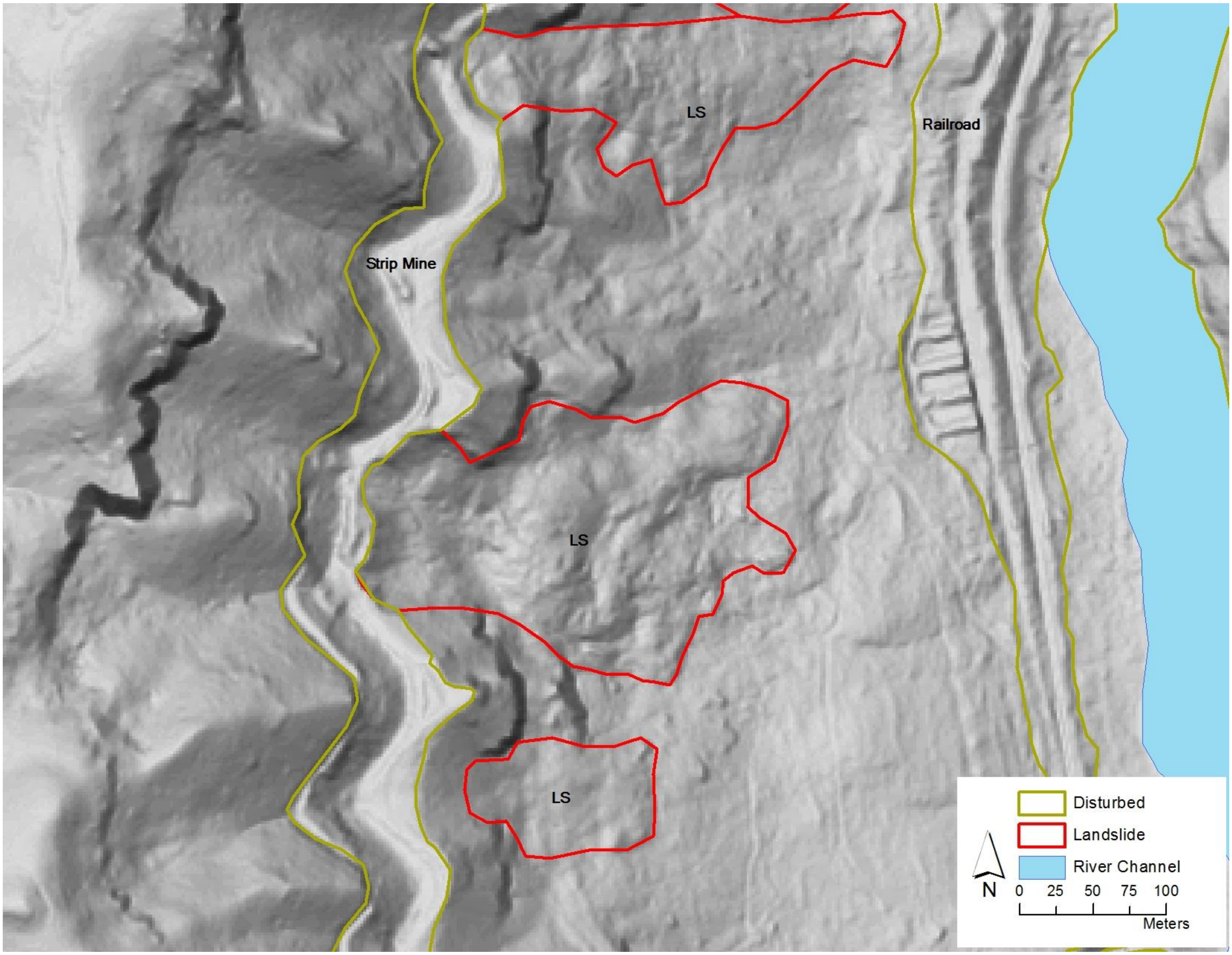

Figure 38. Elverton landslide in middle NERI.

Figure 39. Historic Photograph of Mann's Creek landslide.

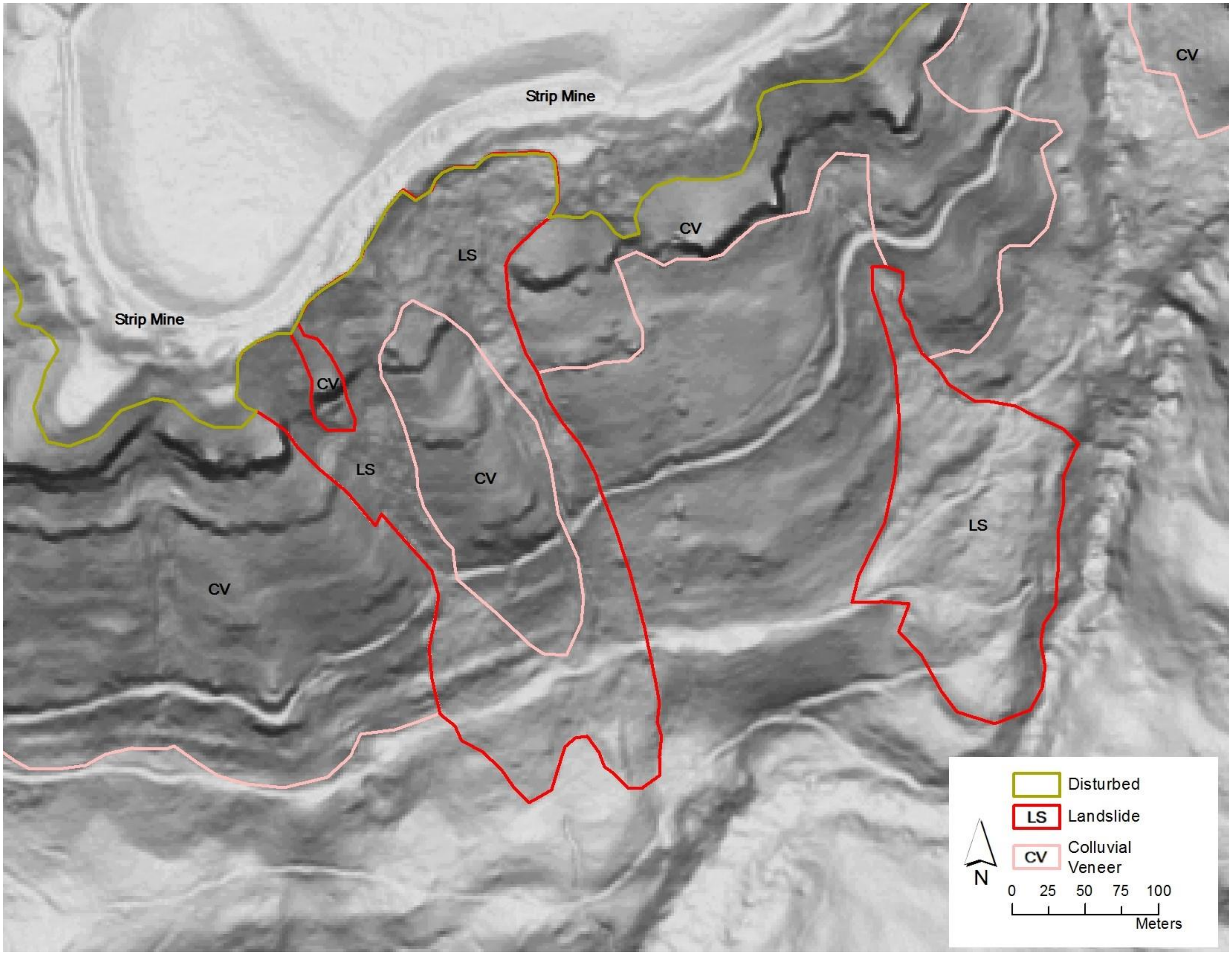

Figure 40. Mann's Creek landslide in middle NERI.

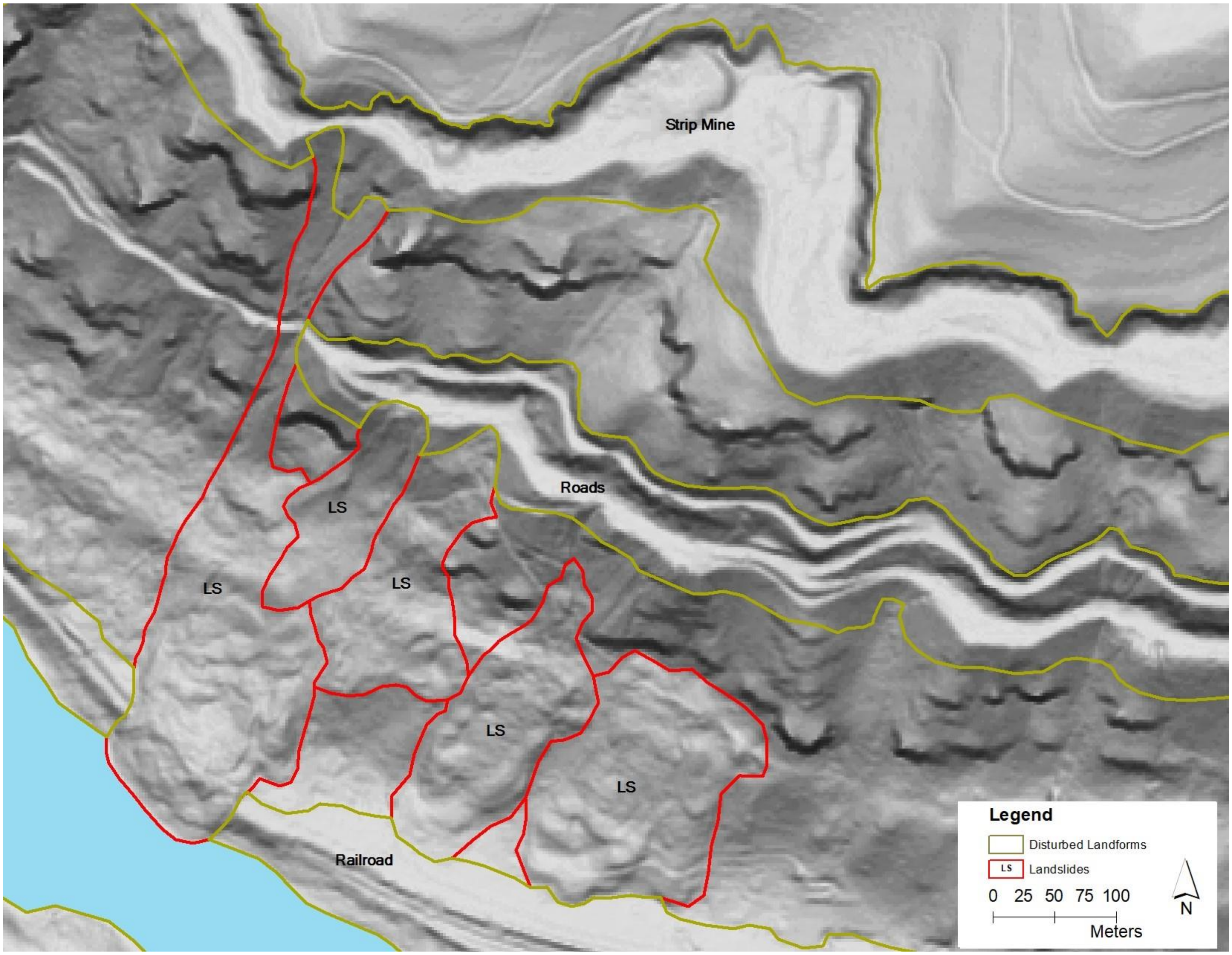

Figure 41. Rush Run Mine landslide complex in middle NERI.

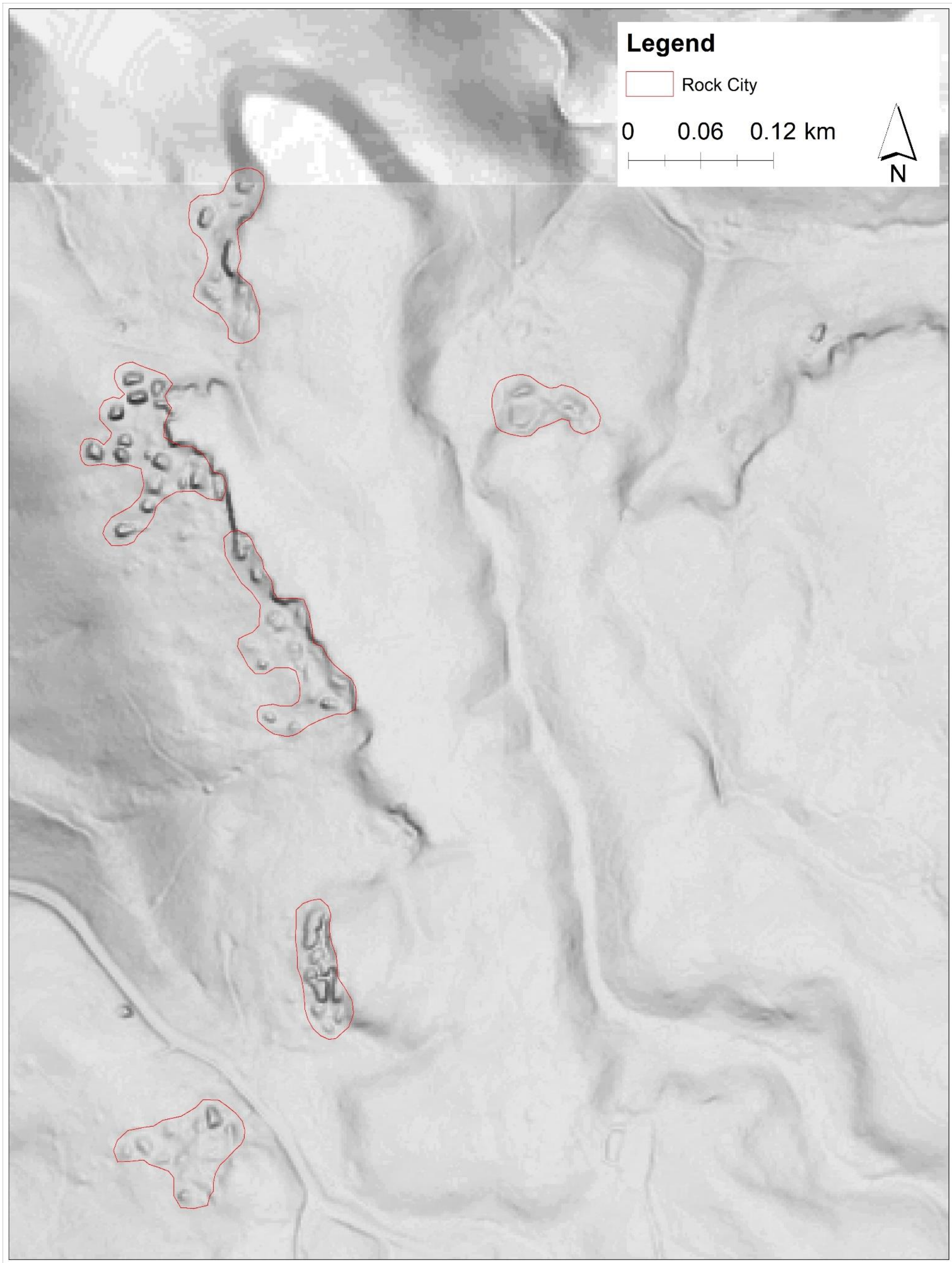

Figure 42. Rock cities located in upper NERI.

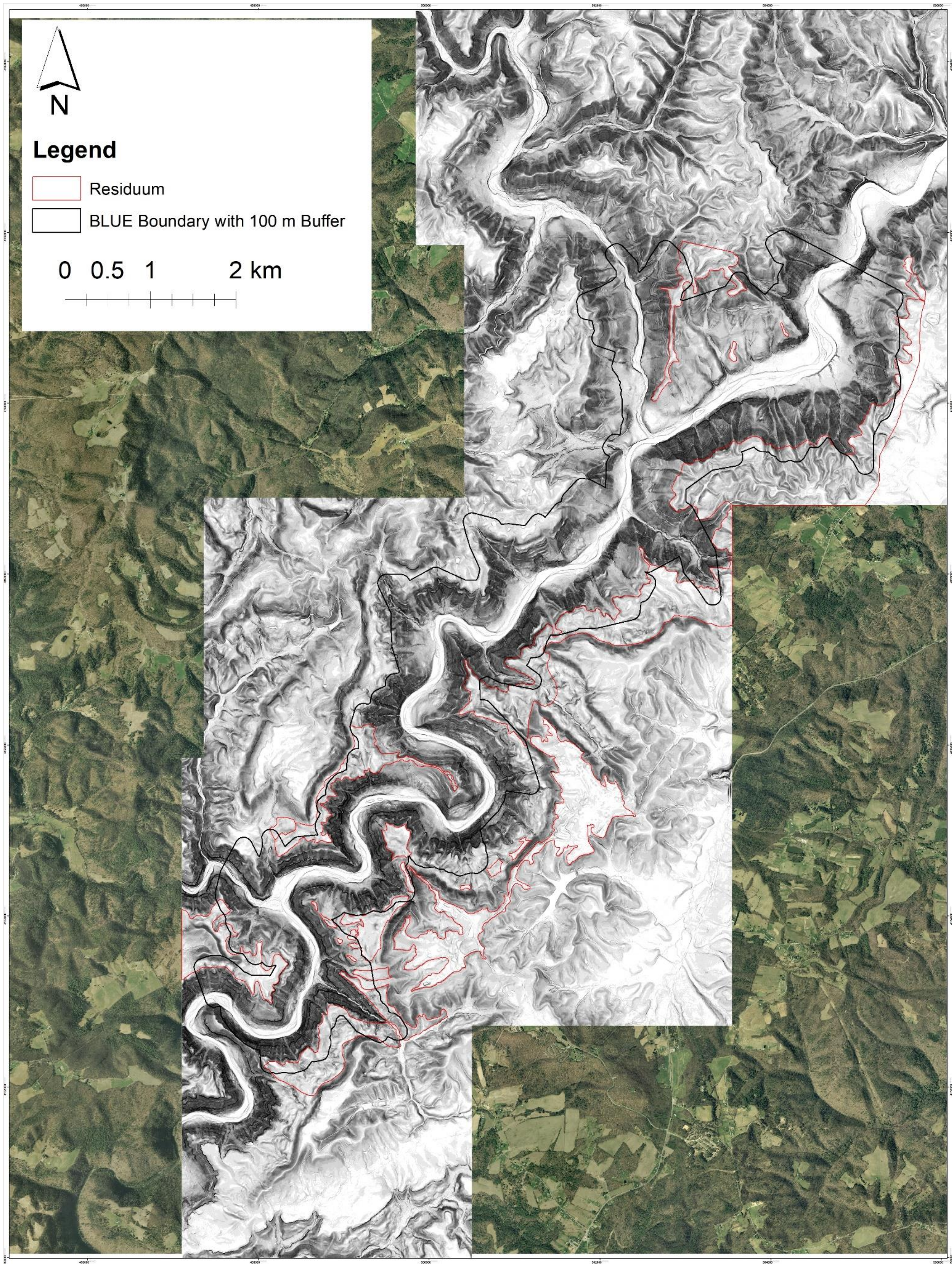

Figure 43. Residuum in BLUE.

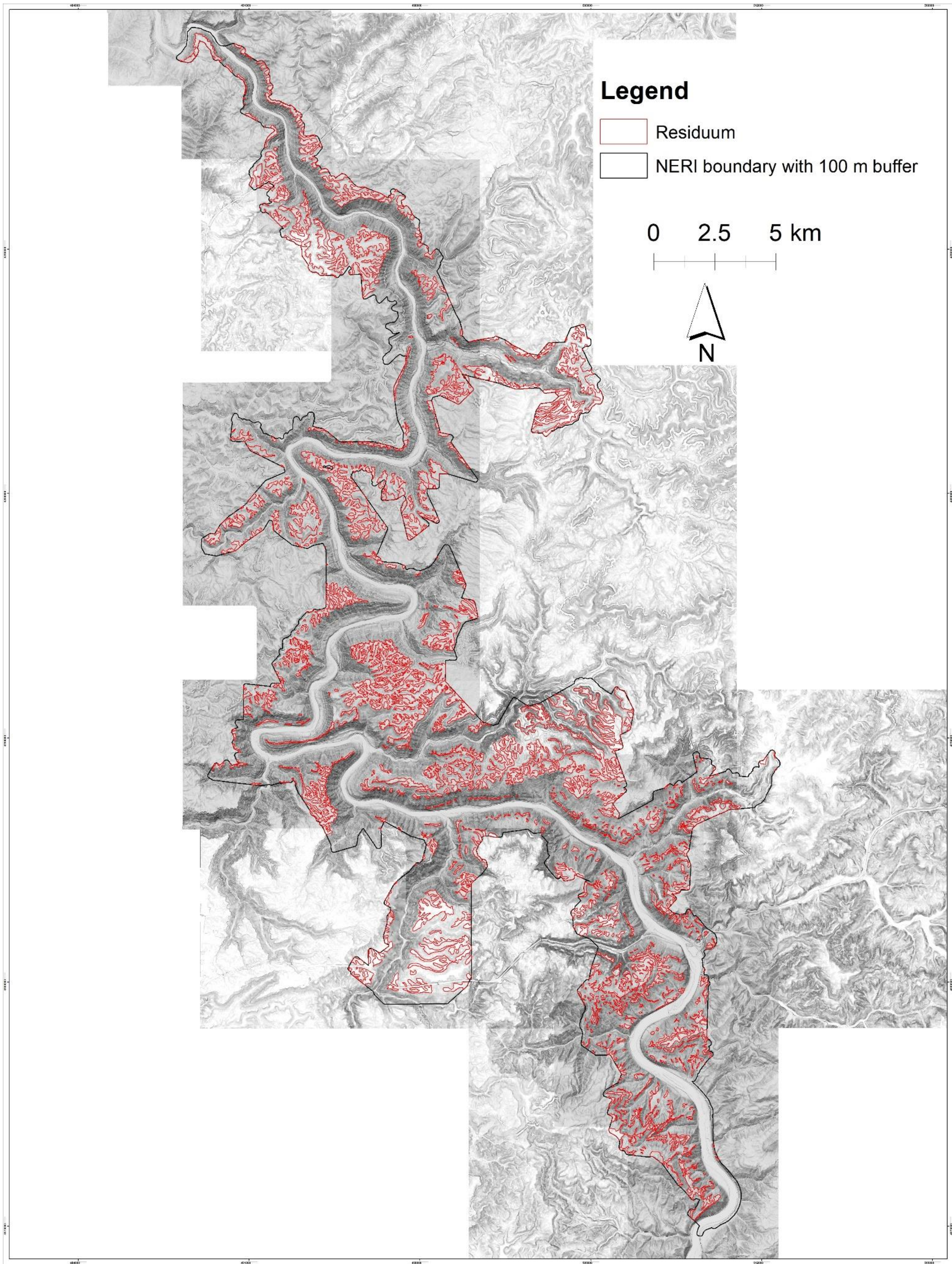

Figure 44. Residuum in NERI.